A COMPREHENSIVE INVESTIGATION OF THE VLF LONG RANGE NAVIGATION SYSTEM

By

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THESIS

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ABSTRACT

The highly stable propagation characteristics of VLF transmissions make them an ideal source of world-wide navigation data. The arrival phase of a VLF signal is continuously compared with a local standard. The change in the phase difference between the received signal and the local standard is converted to relative motion with respect to the VLF transmitter.

This investigation concerns itself with the development as a whole of the VLF navigation system. Refinements are made in the antenna system and the antenna signal processing. In addition, navigation procedures, tables, and forms are presented for system use.

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I. INTRODUCTION

Very low frequency transmissions form the basis of a very accurate long range navigation system. The characteristic of these transmissions that make them ideal for such a use is that their arrival phase at a point distant from the transmitter is both stable and predictable.

The VLF wave propagates through a waveguide formed on one side by the ionosphere and on the other side by the surface of the earth. The phase of the received signal (the carrier frequency) at some point distant from the transmitter remains constant as long as the propagation path (waveguide) or the distance from the transmitter does not change. With the onset of darkness, the ionosphere height increases and modifies the waveguide, causing a change in the observed arrival phase. However, the observed arrival phase will return to its original value when the entire propagation path is again in daylight, and the waveguide assumes its initial dimensions.

With the addition of two stable oscillators, one at the transmitter to serve as a reference for the master oscillator, and the second at some remote receiving site, motion of the receiver can be detected by observing the phase of the received signal as compared to the local oscillator. By commencing to track a transmitter signal in this manner from

a known geographic position, the navigator continuously has one line of position. Proper selection of a second transmitter will result in a second line of position crossing the first, and an electronic fix.

The next section presents the background of this system, and the basic work accomplished in its development. Chapter III goes on to present an explanation of mode theory, which describes the propagation mechanism. This discussion leads to the basis of the system stability, and hence its accuracy. Three basic problems are encountered in the use of this navigation system. These are examined in general in Chapter IV. The problems are long path signal contamination, prediction of the diurnal shift, and the conversion of phase information into geographic positions. Each is treated respectively in Chapters V, VI, and VII with their solutions. Chapter VIII sets forth the system, and treats the units from an individual component view as well as a discussion of the system as a whole. Chapter IX presents the proposed procedures for use of the system.

II. BACKGROUND

The development of the long range VLF navigation system starts with Blackband [1] and Stanbrough [2], who both used this method experimentally with good results. Woods Hole Oceanographic Institute has developed a table of geographic positions [3] which contains bearings and distances to various VLF transmitters. While this table appears to be the initial effort in this line, the geographic positions are each one degree of latitude and longitude apart, a spacing too great for general navigation use.

Lake [4] conducted a general investigation of this VLF navigation system, covering the basic propagation, phase-tracking receivers used, and general navigation procedures.

McKay and Preston [5] covered in depth the factors which degrade the system accuracy, and developed the idea of using an antenna with a cardiod-shaped radiation pattern to reject the long path signal which could contaminate the desired signal in some cases.

Roeder [6] developed an antenna system producing a cardiod-shaped pattern utilizing two loops and a whip with the associated equipment necessary to electronically rotate the resulting pattern.

This paper will bring together the efforts of Stanbrough, Lake, McKay, Preston, and Roeder to result in a system

for long range VLF navigation. The specific results of this investigation are the development of a practical shipboard unit for use as a long range VLF navigation system, an improved method for predicting the time and amount of diurnal shift, the formulation of a means to generate navigational tables of positions, and the presentation of specific forms and procedures for system utilization.

III. MODE THEORY

The propagation of electro-magnetic radiation in the VLF range is best described by waveguide mode theory. The guide, which channels or contains the wave, is formed by the earth on the lower side, and the ionosphere on the upper side, where the term "ionosphere" refers to the ionospheric height for which the conductivity is equal to 10^{-6} mhos/m.

As in conventional waveguides, many modes, other than the principal mode determined by the physical geometry, exist in the near region of sources and discontinuities. The resulting signal sensed at any point in the field is equal to the vector sum of the individual fields due to the multiple modes present. The higher order modes have greater attenuation factors than the principal mode, and therefore their contributions to the resultant signal decrease as the observer moves away from the transmitter. Table I gives various values of attenuation factors for modes 1, 2, and 3 of a 20 kHz signal [7].

MODE		ATTENUATION FACTOR
n = 1	day	1.5 dB/1000 km
	night	1.6 dB/1000 km
n = 2	day	5.7 dB/1000 km
	night	2.7 dB/1000 km
n = 3	day	>15 dB/1000 km
	night	7.5 dB/1000 km

TABLE I
VLF ATTENUATION FACTORS

As an illustration, examine the 20 kHz signal at 1000 km, 2000 km, and 4000 km from the source, during darkness. At 1000 km, the principal mode (n = 1) is down by 1.6 dB. The second mode is down by 2.7 dB, and the third mode is down by 7.5 dB. At 2000 km, the modes are down respectively 3.2 dB, 5.4 dB, and 15 dB. At 4000 km the principal mode is down by 6.4 dB, the second mode is down 10.8 dB, and the third mode is down 30 dB. Further increases in distance reduce the signal contributions of the higher order modes and they may be neglected from consideration. In general, at distances greater than 4000 kilometers, the effects of higher order modes (n = 2 and greater) can be neglected.

VLF propagation has also been described in terms of ray theory. Both mode theory and ray theory will provide the same results, however the mode theory is better suited in this case.

IV. BASIC PROBLEMS

There are three major problems to be solved before the system can be used for navigation. They are the prediction of the time of occurrence and amount of diurnal shift, the means of nulling or canceling the long path signal when the receiver is in the multipath zone, and the problem of converting phase difference information into geographic motion and position. Each of these areas is discussed briefly below, and examined in detail in following sections.

A. DIURNAL SHIFT PREDICTION

Consider an example where the receiving site is located to the west of the transmitter and both places are in daylight. The recorded phase difference between the received signal and a local oscillator should have a constant value since there is no motion toward or away from the transmitter, and the propagation path is not changing. With the occurrence of sunset at the transmitter, the recorded phase difference at the receiver starts to increase as the height dimension of the earth-ionosphere waveguide increases. The increasing height causes a decrease in the phase velocity. The decreased velocity leads directly to the change or increase in the observed phase difference. The phase difference continues to increase until sunset occurs at the receiving site. This increase in the phase difference is the diurnal shift. With

the propagation path completely in darkness, the phase difference is constant until sunrise occurs at the transmitter. This time the phase difference decreases until it reaches its daylight value where it again tracks constant. Since long range navigation at sea is a 24 hour requirement, it is highly desireable that the amount and time of the diurnal shift be predictable. This in fact can be achieved and will be discussed in a later section.

B. LONG PATH SIGNAL

Utilizing the virtual ionosphere-earth waveguide and the low attenuation factor for the principal mode, the signal radiated from the antenna has three prominent characteristic regions, each being associated with certain sections of the "guide." In an area (circle of radius 4000 kilometers) around the transmitter, the multi-mode zone exists. This region is not suitable for phase tracking due to the many modes present. Therefore, this area is not useable for navigating. From the multi-mode zone outwards from the transmitter is the single mode zone which is useful for phase tracking, and likewise for navigation. The single mode zone extends to a region which surrounds the antipode of the transmitter. Herein is the multi-path zone. This region exists since the transmitter radiates its energy omnidirectionally. Therefore, in the area of the antipode, two signals are possible, the direct or short path signal, and the long path signal, that is one that has travelled more

than halfway around the world. The presence of these two signals can contribute major navigational errors if they are not processed with care. The situation can go from a mild contamination of the desired signal to complete dominance of the undesired signal. Of particular concern is the case where minor errors could be introduced into the receivers by the presence of this long path signal, and these would not be immediately detected by the navigator since the system would continue to track in the proper direction.

The degree of contamination will be determined by the lengths of the two signal paths, and the signal attenuation factors for each path. In general, seawater paths have smaller attenuation factors than land paths, and daylight paths have greater attenuation than darkness paths. Therefore, a combination of darkness and seawater for the long path can provide a signal of comparable strength to that of the short path where it may have a significant portion over land and in daylight.

It is highly desirable to use the multi-path zone in that it is also a single mode zone, and has very stable signals for phase tracking. If this region was not used, the system would be significantly restricted. The use of an antenna system with a directive pattern which discriminates against the undesired signal would solve this problem.

C. TABLES

In order to convert the phase change (receiver information) into geographic motion and position, suitable tables, similar

to those existing for LORAN A, must be generated to allow plotting the ship's position on charts. These tables should include known geographic positions, and bearings and distances (expressed both in nautical miles and microseconds) to transmitting stations. The geographic positions should be spaced no greater than thirty miles apart.

D. MINOR PROBLEMS

Four minor problems associated with maintaining an accurate plot of a ship's position are:

a. Cycle slipping

b. Transmitter outage

c. Frequency offset of the transmitter master oscillator

d. Sudden ionospheric disturbance (SID).

Each of the above should pose no problem for a navigator with a minimum familiarity with this system. Cycle slipping refers to the situation when the receiver is tracking a changing arrival phase condition, and drops behind in indicated phase by 360 degrees or integer multiples thereof. This would generally occur only where the phase difference is changing rapidly. This could only happen at the onset or offset of the diurnal shift. The type of receivers used in this investigation allows the operator to "drive" the receiver back onto the proper cycle if slipping does occur. The operator also has an option to choose a shorter time constant for the receiver to insure that cycle slipping does not occur.

Scheduled transmitter outages are no problem. Normally, these outages are scheduled, and the navigator should have shifted the receiver to an alternate transmitter. Tracking of a transmitter can commence from any known position. By selecting an optimum time, the shift of stations can be made without difficulty, and without a loss in position accuracy. Since a prudent navigator values a three lines of position fix, risk from this and other anomolous outages can be minimized by tracking three transmitters at all times.

Frequency offsets of transmitter master oscillators are scheduled sufficiently in advance that the amount of the offset and date and time of its application will be promulgated to all concerned. The navigator at sea need only make an appropriate correction for his calculations.

Sudden ionospheric disturbances are caused by solar flares, magnetic storms, and high altitude nuclear blasts. The duration and magnitude of the distrubance will depend on the duration and magnitude of the disturbing phenomena. In general the disturbances are not intense, and of short length. In any case, their effect is to lower the ionospheric height, causing an increase in the phase velocity of propagation. This increase would make the transmitters being tracked appear closer to the ship. Continuous chart recorders would help the navigator to recognize the onset of a distrubance. There would be a rapid decrease in the displayed phase difference information. Under this circumstance, a dead reckoning track should be plotted from the last accurate

position. Subsequent positions may be determined by celestial navigation or other means. These positions compared with the system performance will provide an indication of when the ionospheric behavior has returned to normal.

E. PROPAGATION CONSIDERATIONS

The navigator, in using this system, must understand certain VLF propagation characteristics to intelligently assess the validity of signals under various circumstances. For example, it must be realized that the velocity of signal propagation is dependent on the height of the ionosphere and also on the signal path. The signal path is classified as to being over seawater, land, or ice. If the path is over ice, the ground conductivity is such that the wave behaves as if it were propagating over land. Hereafter, reference will be made only to the land path due to the similar behavior of propagation over ice. Since this is a relative navigation system, the percent of signal path over land or seawater has no effect on the system ability to fix a position during daylight hours. However, as it will be seen in a following section, the observed diurnal shift for the land portion of the path is not proportional to that for the seawater path. Therefore, the navigator must be cognizant of the amount of propagation path over seawater, and over land to accurately predict the diurnal shift corrections. If a polar path is being utilized, he must also be knowledgeable of the extent of the ice pack for that particular time of the year.

As an example of the differences in velocities of signal propagation, TABLE II demonstrates their magnitudes for a 20 kHz signal under various conditions. The four starred conditions denote the standard ionospheric conditions. Using

	Phase Velocity (m/s)	Day/Night	Path	Ionosphere Height (km)
*	2.95×10^8	Day	Seawater	70
*	2.94×10^8	Night	Seawater	90
*	2.97×10^8	Day	Land/Ice	70
*	2.96×10^8	Night	Land/Ice	90
	2.96×10^8	Day	Seawater	60
	2.95×10^8	Day	Seawater	80

TABLE II

PHASE VELOCITIES UNDER VARIOUS CONDITIONS

these velocities one arrives at the standard conversion value of 6.18 microseconds per nautical mile for daytime propagation over seawater. Night propagation over seawater has a conversion of 6.22 microseconds per nautical mile.

Navigation tables are calculated later in this investigation. The entries are on the basis of 6.18 microseconds per nautical mile. They may be adjusted for the second conversion (6.22) by multiplying the distances expressed in microseconds by a factor of 1.006.

V. ANTENNA SYSTEM

The ability to discriminate against the long path signal when the ship is located in the multi-path zone is the function of the directive antenna system. An ideal system should have small, lightweight, and stationary elements. However, normal multi-element arrays utilized as antennas in the VLF range would be of such size that only a land-based installation could support such configurations.

The use of a loop antenna, whose vertical plane is pointed at the transmitter, provides a means of attaining the above favorable antenna properties with bi-directional sensitivity. When this pattern is coupled with a properly phased whip signal, a cardiod-shaped pattern results with a null opposite to the bearing of maximum signal gain.

The loop antenna output is the difference between the signals detected by opposite legs of the loop. A signal or voltage difference exists due to the spatial separation of the two antenna legs. If the antenna's orientation is changed, the magnitude of the detected difference signal decreases as the spatial separation (and hence the phase difference) with respect to the wave front decreases. Therefore, a null occurs when the plane of the antenna is perpendicular to the wave front.

To attain the cardiod shaped antenna radiation (field intensity) pattern, the whip antenna signal is matched in

magnitude to that of the loop antenna, but with a 90 degree phase lag. The result of adding the two antenna outputs is a signal of twice the strength in the preferred direction, and a null 180 degrees from the maximum. Figure 1 is a composite of the radiation patterns of the single loop antenna, the whip antenna, and the resulting cardiod shaped pattern.

Since the cardiod-shaped pattern is the result of a phase addition, and the navigation system utilizes changes in phase difference to detect motion, the change in phase across the axis of the pattern is of major concern. McKay and Preston [5] demonstrated both theoretically and experimentally that a "zero phase change window" does exist on the pattern axis. This investigation also confirms the presence of this window. Since this window is of finite width, errors will not be introduced in the system if the antenna pattern is not pointed exactly at the transmitter. If the resolver rotor indicates a direction within 5 degrees of the transmitter bearing, no appreciable error exists. McKay and Preston also have shown that the pattern null is down 30 dB for a sector of 40 degrees width. This investigation again confirms this performance. Therefore, any observed phase changes are indicative of the motion of the receiver toward or away from the transmitter and not due to a phase change introduced by the antenna system.

The use of a single loop and single whip for phase tracking is impractical in that only one station may be tracked for each antenna installation, and also a sizeable and

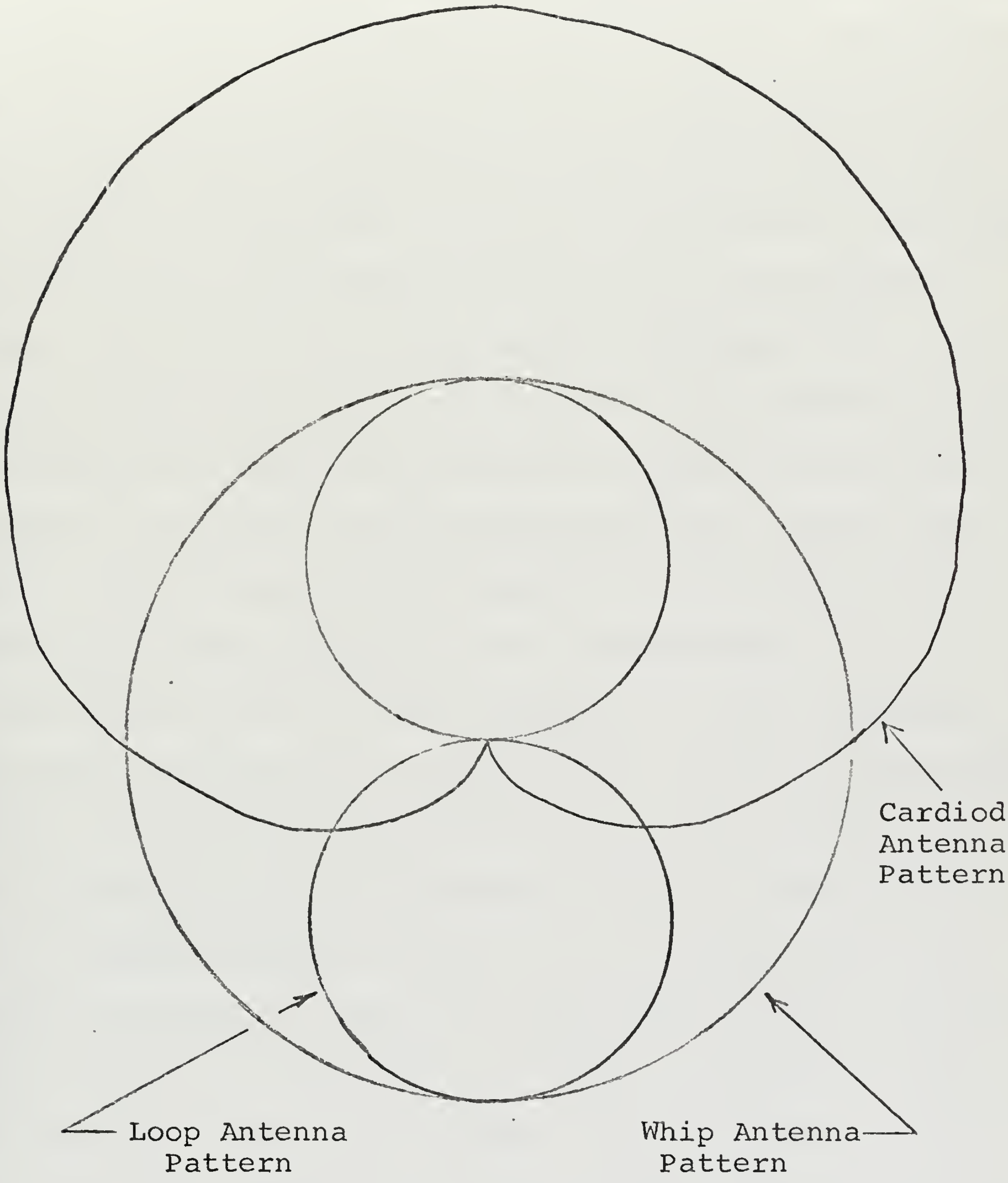

Figure 1. Composite Antenna Patterns.

massive antenna drive system would be required to continuously point the loop antenna. Roeder [6] developed a means by which 2 stationary loops duplicate the performance of a rotatable single loop. As seen in Figure 2, the 2 loops (mounted concentrically and perpendicular to each other) drive field coils mounted in quadrature. The field generated in each coil is proportional to the signal sensed by the corresponding antenna. The rotor will sense the maximum signal when positioned at an angle that corresponds to the direction of signal arrival. The antenna radiation pattern illustrated in Figure 2.c is obtained by turning the rotor through 360 degrees. This antenna system duplicates the behavior of a single loop pointed directly at the transmitter.

As a demonstration of the feasibility of this approach, Roeder used goniometers in place of the field and sense coils to test a system capable of tracking two transmitters. A means of positioning the goniometer rotors was required to keep the antenna patterns pointed at the transmitters while the ship maneuvered. This was accomplished by use of a gyro compass signal input to a power amplifier which fed a servo motor attached to the rotor shafts. With the addition of a whip antenna and cardiod units, the proper radiation patterns were formed.

In part, this investigation was directed toward the realization of a more practical shipboard installation. To reach this aim, the six feet diameter loop antennas used by Roeder were replaced by a submarine VLF crossed loop antenna.

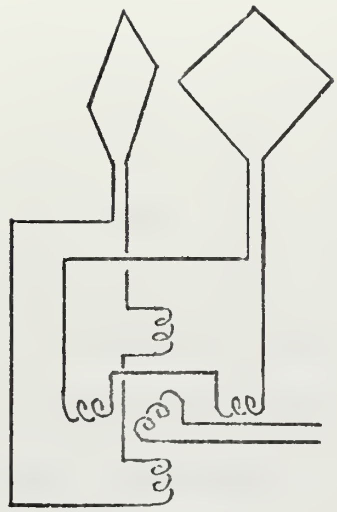

Figure 2.a. Basic Schematic.

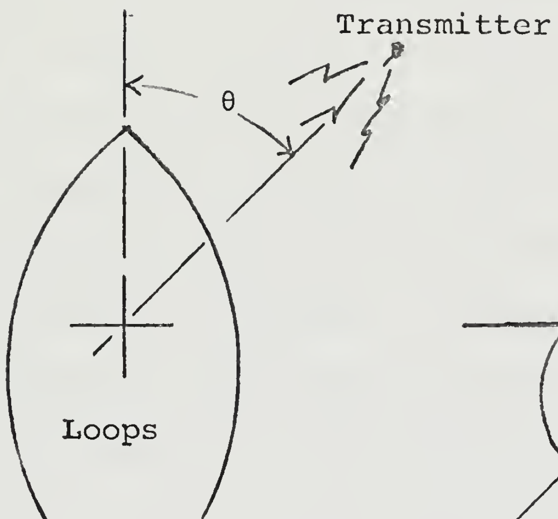

Figure 2.b. Geographic Picture

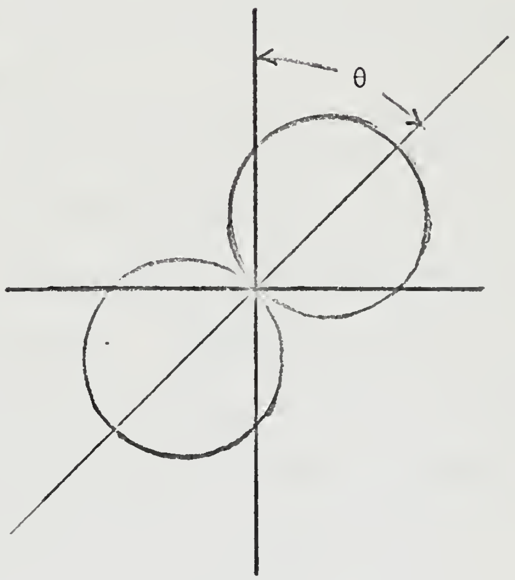

Figure 2.c. Antenna Pattern.

Figure 2. Effective Single Loop Antenna System.

This greatly reduces the size of the topside or mast-mounted unit. An order of magnitude decrease is possible since the submarine antenna loops are wound on ferrite cores.

In place of goniometers, precision resolvers were used with a reverse signal flow. Again, as in the case of the antenna, a much smaller physical size is realizable for an operational unit, and as a result allows the direct use of a gyro repeater signal for driving or positioning the rotors without the need of a power amplifier.

The gyro compass repeater input can be either 120 VAC, 60Hz or 120 VAC, 400 Hz. The synchro receiver drives a local compass card. Two other compass cards are geared to the driven unit. A means of securing the rotors of the resolvers to the compass cards is provided through a bearing pointer. The bearing of the station to be tracked is indicated by the pointer when the unit is in operation.

Audio amplifiers are used to boost the VLF signal level for the two loops' inputs into the resolvers. The two amplifiers feed four windings. Each amplifier feed corresponding windings, one in each resolver. Separate gain controls are present for each winding in each resolver. More resolvers may be fed to allow a capability to simultaneously track more transmitters. Caution should be exercised to insure that sufficient signal energy is available at the output of the amplifiers for this purpose.

In order to combine the loop and whip signals properly, commercial cardiod units are used in this system. These units are manufactured by TRACOR, Inc. of Austin, Texas.

They provide a means to vary independently the magnitude and phase of the whip signal. The loop signal may be reversed in phase. The output of the two cardiod units furnish the input or antenna signals for the VLF tracking receivers.

Figures 3, 4, and 5 represent the results of tests performed on the antenna system using VLF transmitters NAA, NBA, and NPM as radiating sources. Each of the figures contain two plots. A circular plot of the field intensity demonstrates in each case that the axis of the pattern points in the direction of the transmitter. Also, the cardiod-shaped patterns are well defined, and clearly exhibit the null and severe attenuation in the reverse direction. The second plot is the measure of the phase distortion error. These plots are centered on the bearing of the transmitter and span a sector of 20 degrees. These measurements confirm the existance of the "zero phase change window" on the pattern axis, and the proper formation of the antenna pattern.

The tests were conducted in the following manner. Two receivers were used to track a transmitter. One receiver used the antenna system as a signal source, and the second receiver used a whip antenna only. This second receiver served as a reference for comparison with the performance of the antenna system channel. The field intensity was measured every 5 degrees of rotation of the resolver rotor, and plotted as shown in Figures 3.a, 4.a, and 5.a. For the phase distortion error measurements, the phase difference data of both receivers was compared as the resolver rotor position was changed. This information is presented for a 20 degree window in Figures 3.b, 4.b, and 5.b.

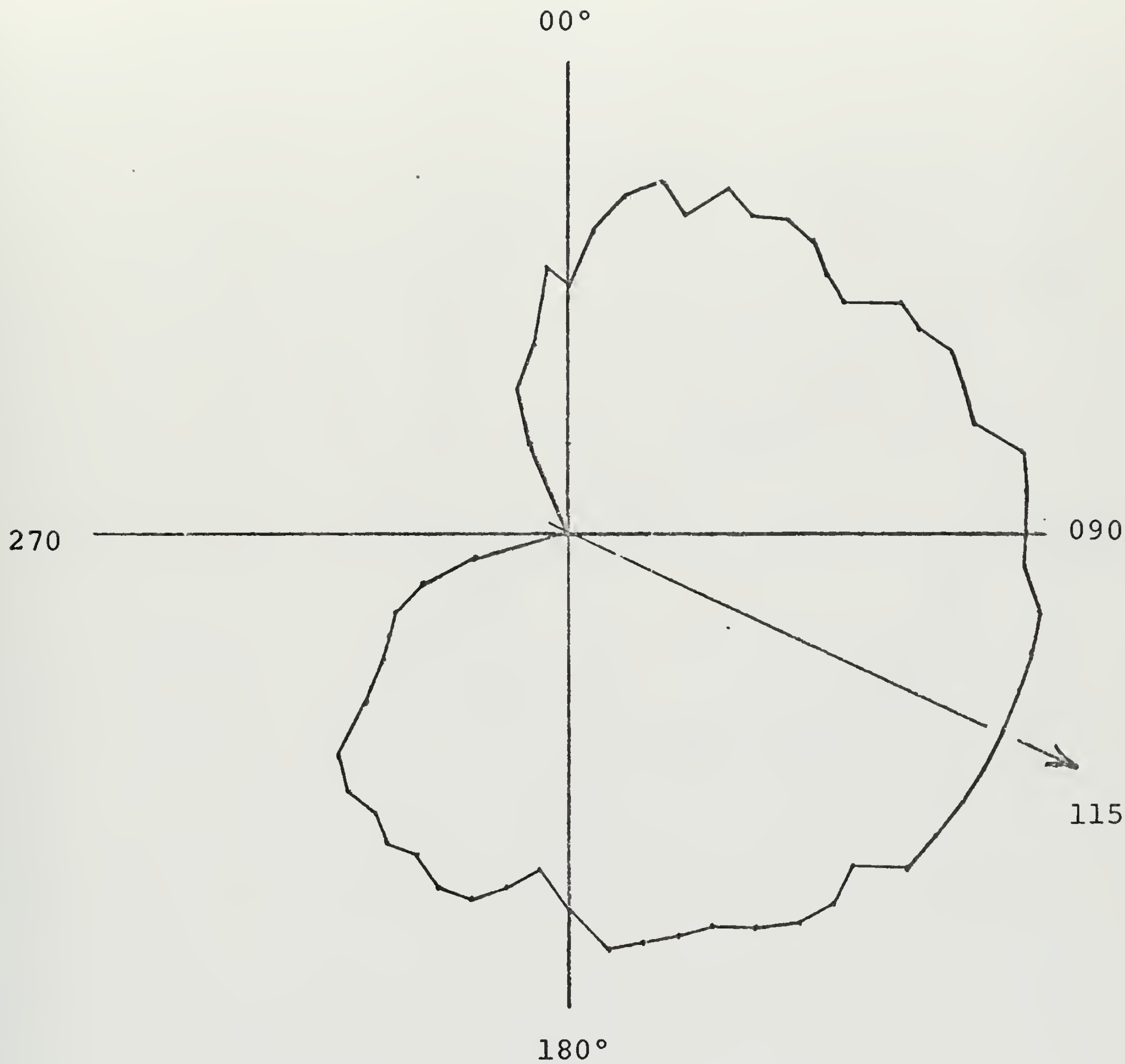

Figure 3.a. Intensity Pattern.

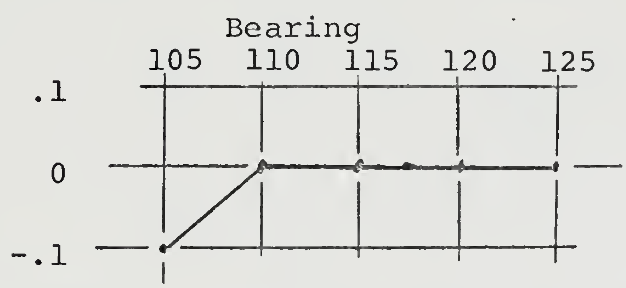

Figure 3.b. Phase Distortion Error in Microseconds.

Figure 3. Antenna Field Intensity Pattern and Phase Distortion Error Source - NBA, Bearing 115.

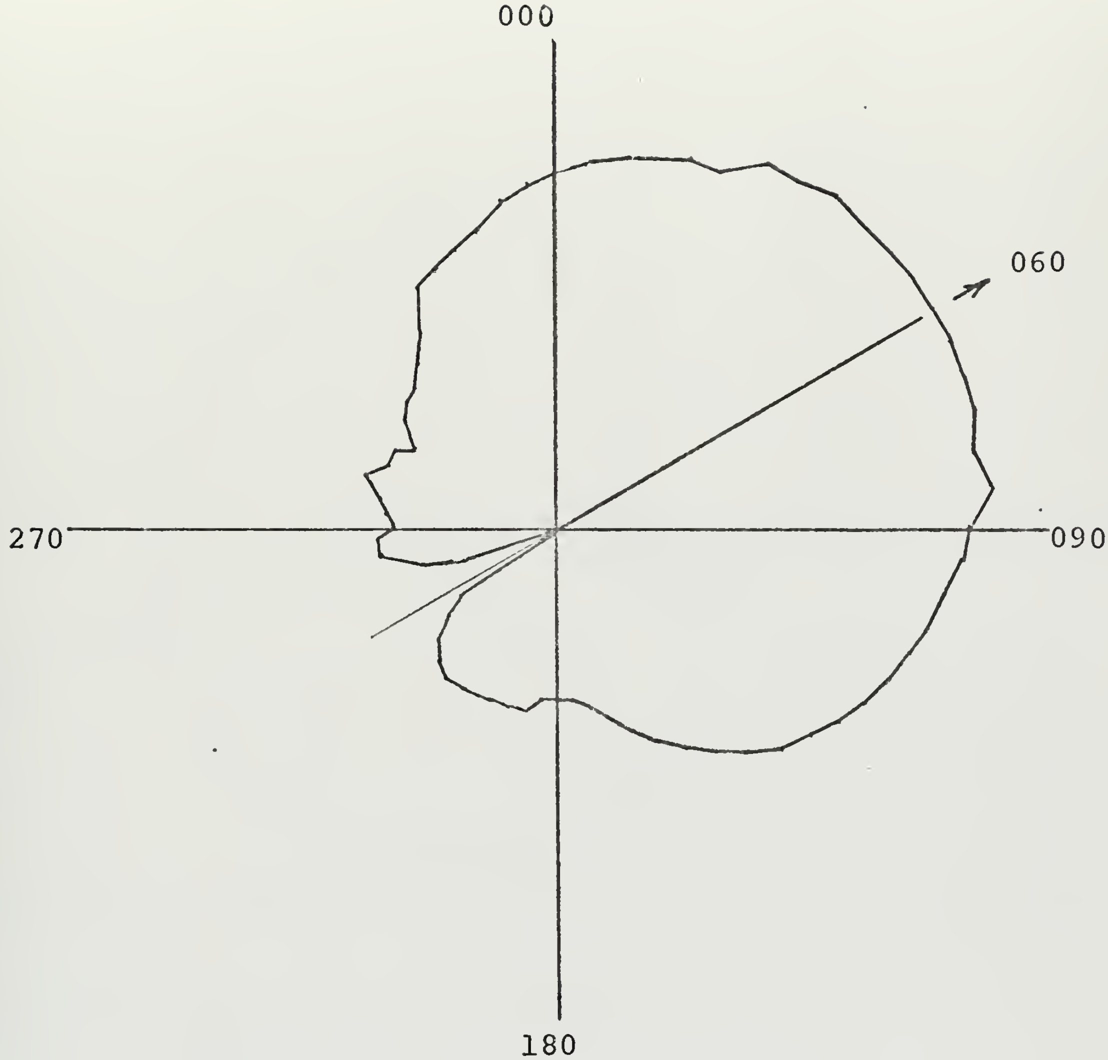

Figure 4.a. Intensity Pattern

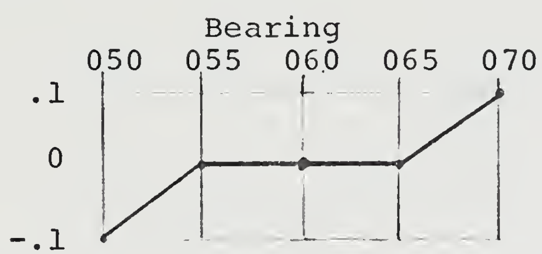

Figure 4.b. Phase Distortion Error in Microseconds.

Figure 4. Antenna Field Intensity Pattern and Phase Distortion Error Source - NAA, Bearing 060.

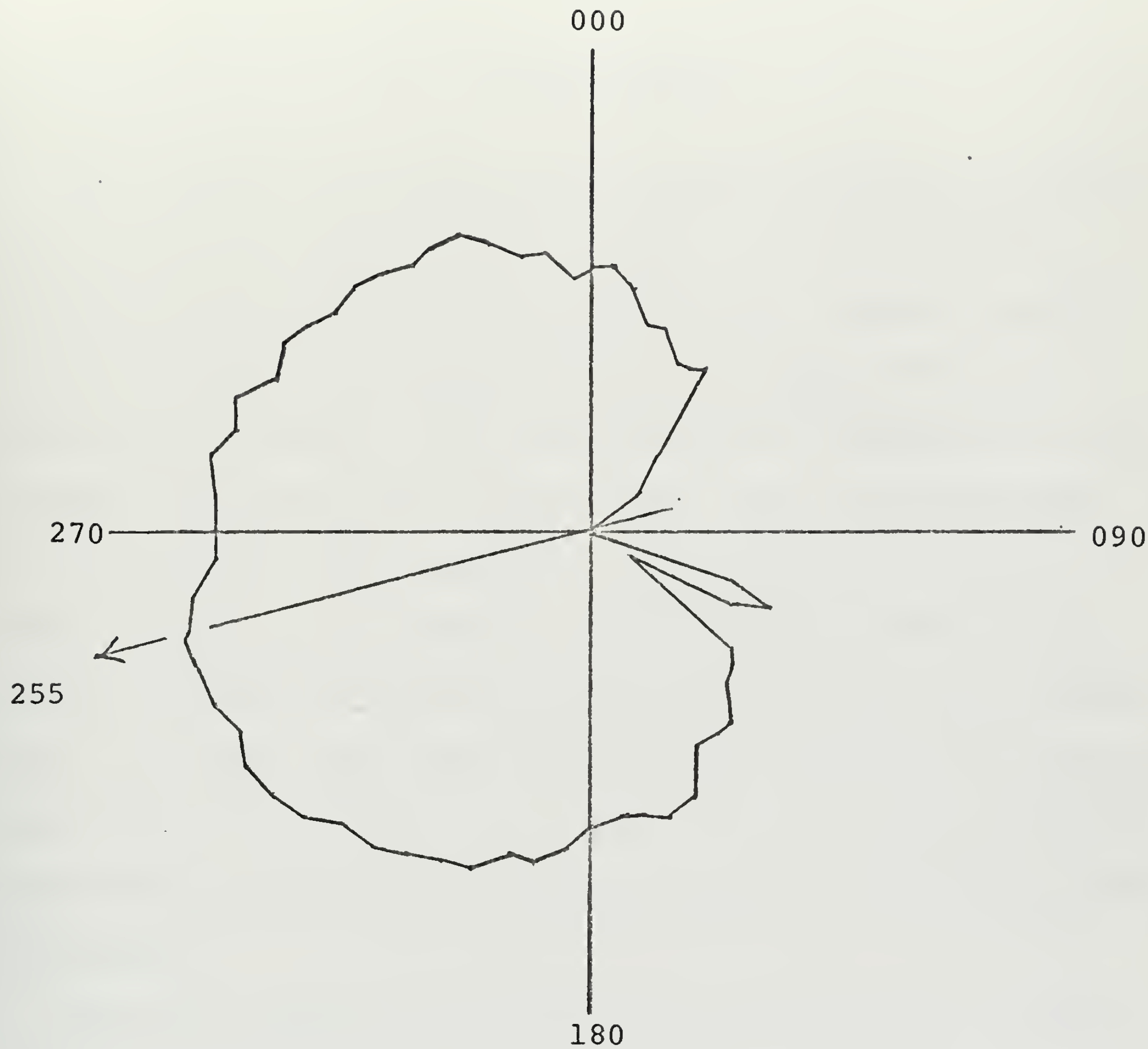

Figure 5.a. Intensity Pattern.

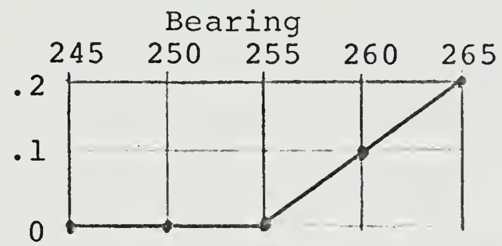

Figure 5.b. Phase Distortion Error in Microseconds.

Figure 5. Antenna Field Intensity Pattern and Phase Distortion Error Source - NPM, Bearing 255.

VI. DIURNAL SHIFT

The observed relative phase difference between the stable local oscillator and the received VLF signal (hereafter referred to as the "phase difference") at a remote receiver increases as the ionospheric height increases with the occurrence of sunset. The phase difference settles at a new constant value when the complete path from the transmitter to the receiver is in darkness. The reverse process of sunset is observed at sunrise. This change between the two constant values of the phase difference is called the diurnal shift. In order that the navigator may determine his position from sunset to sunrise, the diurnal shift must be predictable in the time of occurrence, and the amount of additional phase difference.

McKay and Preston [5] approached this problem by calculating various relative phase velocities for different conditions. A more direct solution to this problem is a combination of the work of Wait [8] and Brady and Crombie [9]. Wait's work, which is described in the next paragraph, gives us the amount of diurnal shift, and Brady and Crombie provide the means to calculate the time of sunset and sunrise at the height of the ionosphere. The work of Brady and Crombie will be treated more fully in a following section on navigation procedures.

This solution assumes that the daily phase difference variation for a stationary receiving site can be accurately

represented by a trapezoid as shown in Figure 6. For this

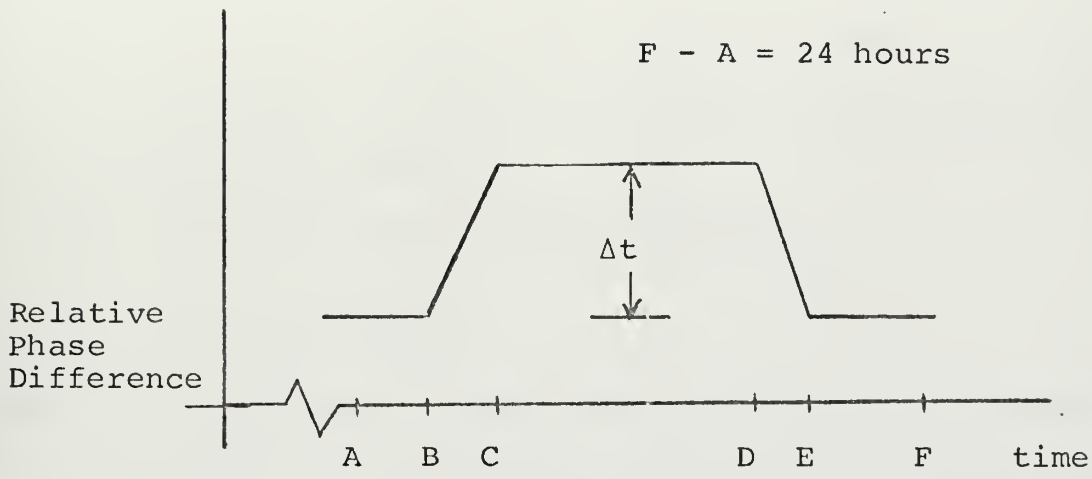

Figure 6. Diurnal Phase Shift.

example, consider the case where the receiving site is to the west of the transmitter. During the period represented by the interval A to B, there is a constant phase difference observed. At the time B, sunset occurs at the transmitter, and the height of the ionosphere starts to increase causing an increase in the phase difference due to the decreasing phase velocity. The phase difference continues to increase until sunset occurs at the receiver. At this time, the waveguide path has again stabilized, and a constant phase difference is observed until sunrise occurs at the transmitter at time D. Then the phase difference decreases until time E when sunrise occurs at the receiver. The phase difference is again at the same value as for the preceding day. If the

receiver was to the east of the transmitter, point B would represent the time of sunset at the receiver and C, the time of sunset at the transmitter. Likewise, D would be the time of sunrise at the receiver, and E would be the time of sunrise at the transmitter. However, the measured value of Δt would be the same in both cases.

Wait developed the following equation

$$\Delta t = \frac{D}{.3} (d/v_n - c/v_d)$$

where Δt is the total diurnal phase shift in microseconds, D is the distance in kilometers between the transmitter and receiver, c is the velocity of light, v_n is the phase velocity of the signal at night, and v_d is the phase velocity during the day, the last three quantities having units of meters per second.

The foregoing presupposed a stationary receiving site. Now, with the receiver located on a ship that is moving away from the transmitter, Figure 6 must be modified by adding point by point a second plot which is a line with a slope equal to N x 6.18 microseconds per hour where N is equal to the speed of the ship in knots in the direction of the transmitter. (Note, the slope is positive for motion away from the transmitter, and negative for motion toward the transmitter.) At the same time, the night or darkness portion of the trapezoid pattern will be modified since Δt varies linearly with D. Therefore, for a more complete picture of the diurnal shift as it applies basically to the VLF navigation

system, Figure 7 is presented with the various portions of the composite process.

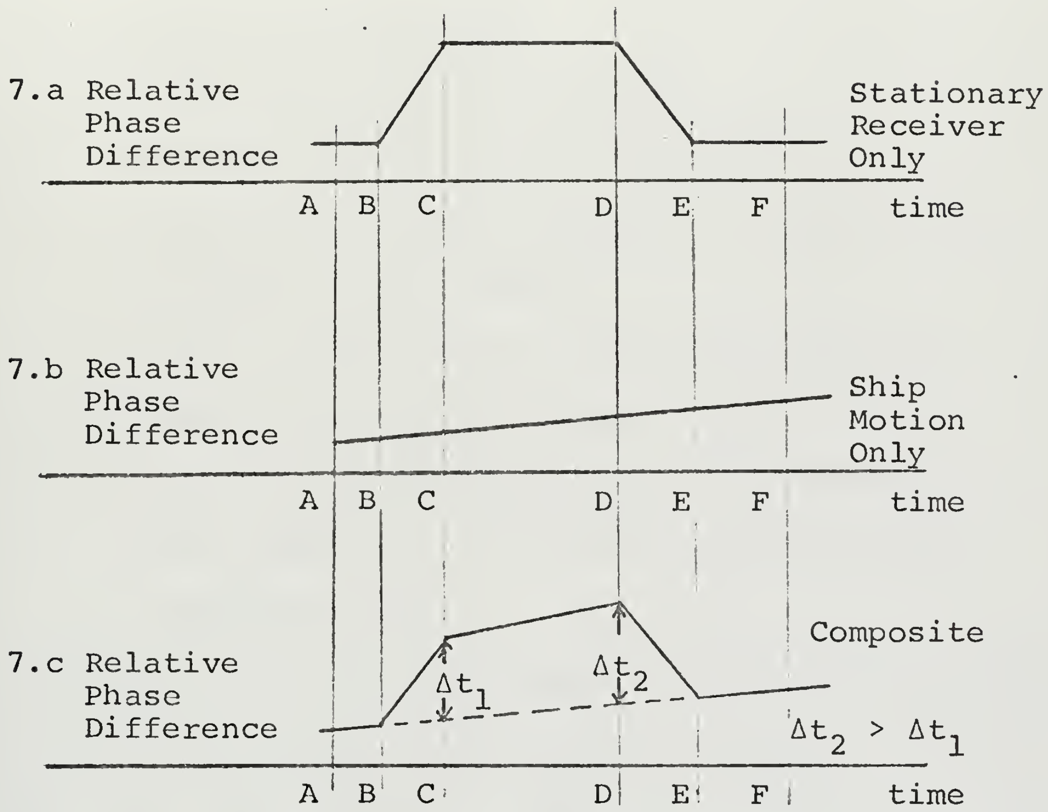

Figure 7. Diurnal Shift with Ship Motion.

Examining Wait's equation, the distance to the transmitter must be known, and ratios of the velocity of light to the phase velocity for both day and night must be determined. The great circle distance can be calculated using methods such as Bowditch [10]. In order to find the velocity ratios, an equation from the Omega System handbook [11] is used:

$$\frac{v_p}{c} = 1 - 0.36 \frac{h_i}{a} + \left[(2\pi n - \varphi_g - \varphi_i) \frac{c}{4\pi\sqrt{2}\ f\ h_i} \right]^2$$

Where

v_p = signal phase velocity

c = free space velocity of light

0.36 = constant chosen to give a good fit

h_i = ionospheric height for which the conductivity is equal to 10^{-6} mhos/m

a = radius of the earth = 6378.155 kilometers

φ_g = phase shift on reflection at the ground

φ_i = phase shift on reflection at the ionosphere

n = mode number ($n = 1$ for the principal mode)

f = frequency in Hz

Initially, an attempt was made to compare the results of the observed diurnal shift with the calculated value of Δt using the above equations. Since the distance was fixed, it was possible to arrive at accurate values for $(c/v_n - c/v_d)$. The measured values did not agree with those calculated.

A second attempt to predict the diurnal shift began with measuring Δt for stations where the propagation path was entirely over land (stations NAA, NSS, and NBA). This resulted in three accurate values for $(c/v_n - c/v_d)$. The heights used for the ionosphere were 70 kilometers for day, and 90 kilometers for night. The constant, 0.36, was replaced by "C", and the equation solved for "C". This resulted in three values for "C" as shown in Figure 8. As an initial interpretation, "C" was represented by a linear function of frequency.

Therefore, the constant for a good fit has been replaced by a linear function of frequency. Using the data from Figure 8, a curve showing the value of C_v versus frequency is plotted as Figure 9 for the land propagation route, where C_v is defined as $(0.53961/0.3)(c/v_n - c/v_d)$. This substitution allows one to use nautical miles directly for the computation of Δt.

The same procedure was followed for sea propagation routes. These results are shown in Figures 10 and 11. A similar curve is shown, Figure 12, which was derived from data presented by Spies and Wait [7]. Figure 13 is an overlay of Figures 9, 11, and 12 to compare the general shapes and slopes of the three curves.

Figures 9 and 11 along with a modified version of Wait's equation, would be used by the navigator in his prediction of

$$\Delta t = D\ C_v$$

the amount of the diurnal shift. In the case where the entire propagation path is over seawater, C_v is read from Figure 11 for the proper frequency. Then, Δt would be equal to the product of C_v and D. If the propagation path for the signal is over both land and seawater, Δt is then the sum of the diurnal shift for the land portion of the path, and the seawater portion of the path. For example, examine the situation where a ship is 6000 miles from the transmitter (f = 22.0 kHz). The seawater portion of the path is 4000

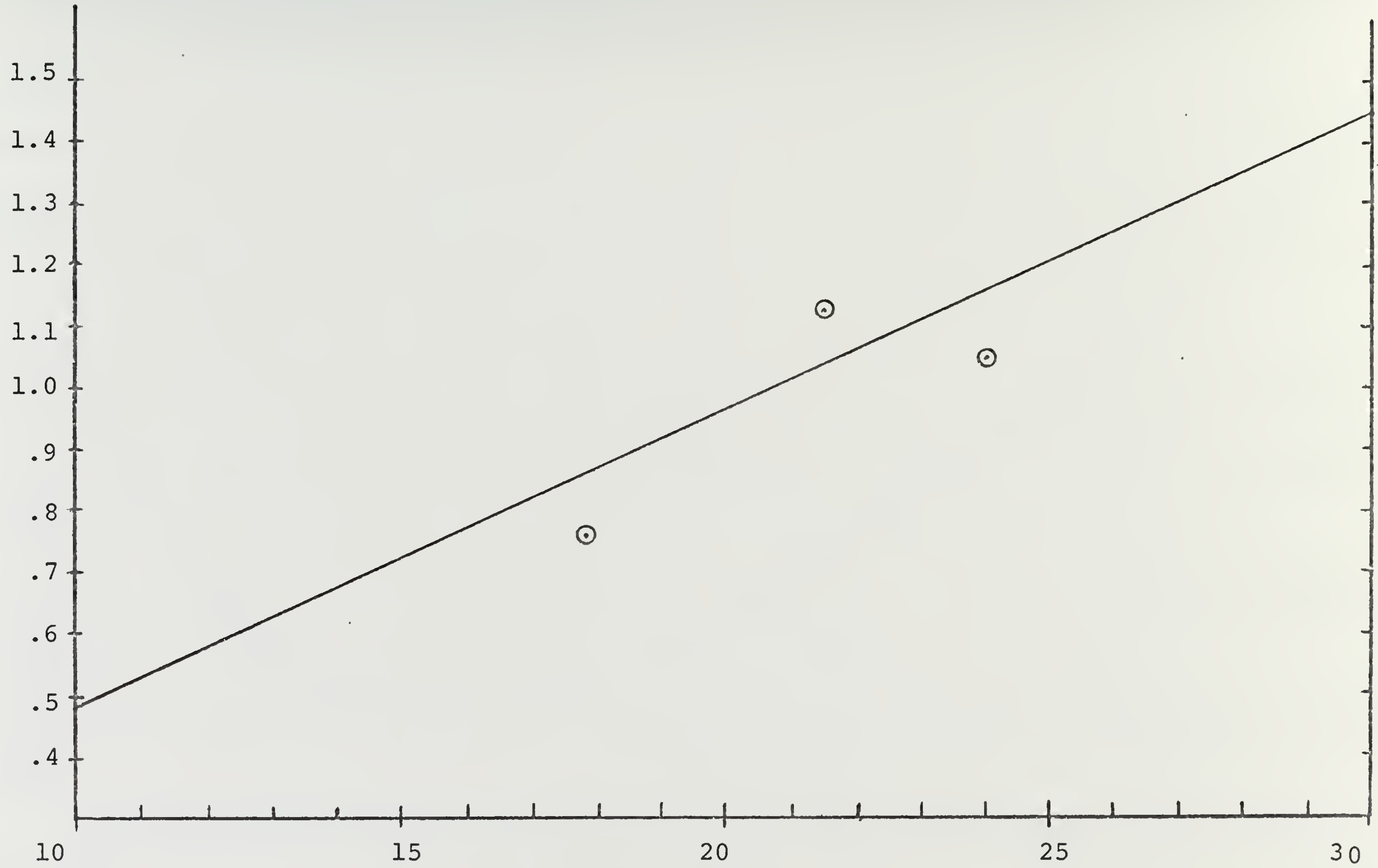

Figure 8. "c" Land Route

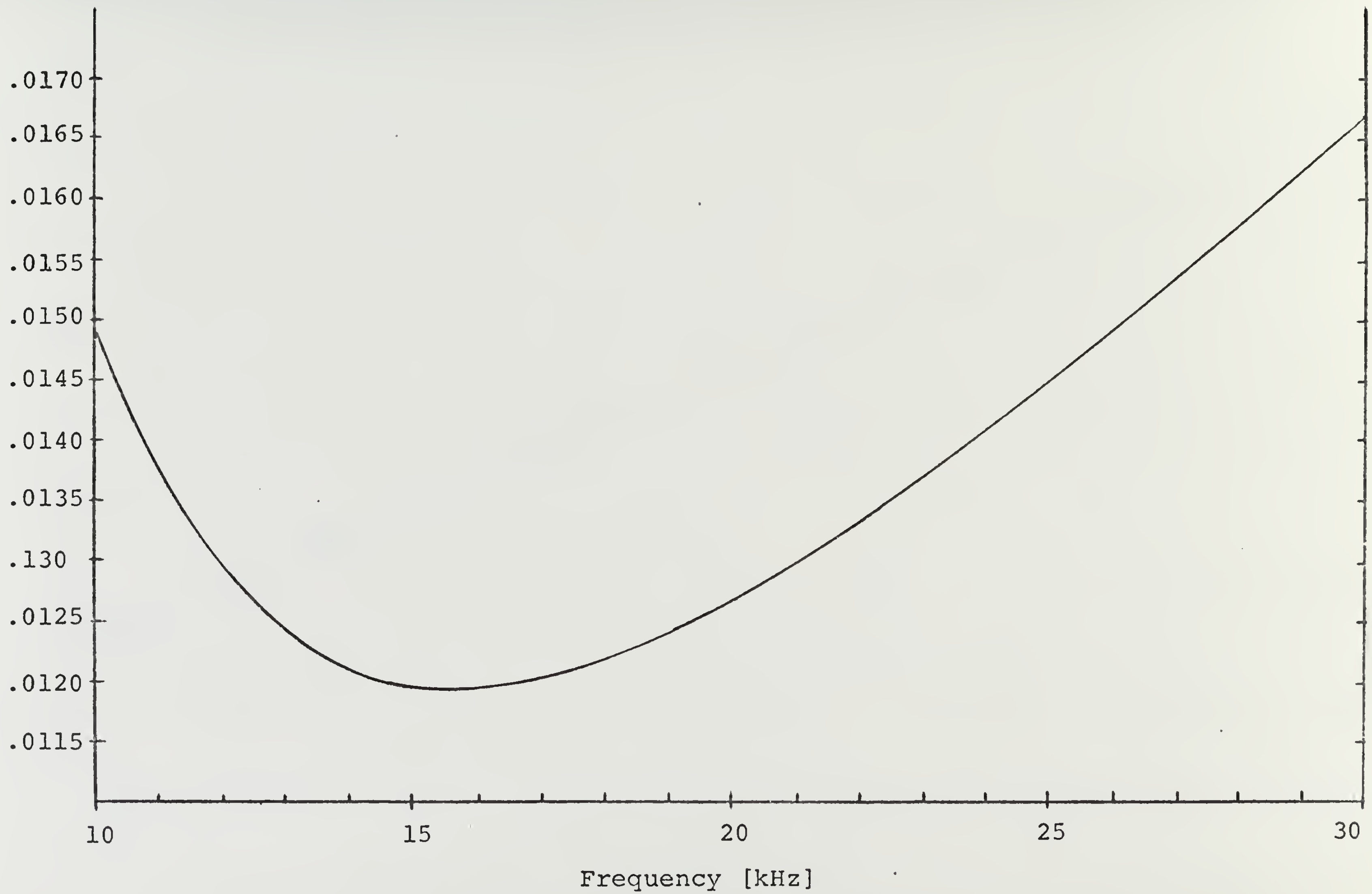

Figure 9. C_v Land Route.

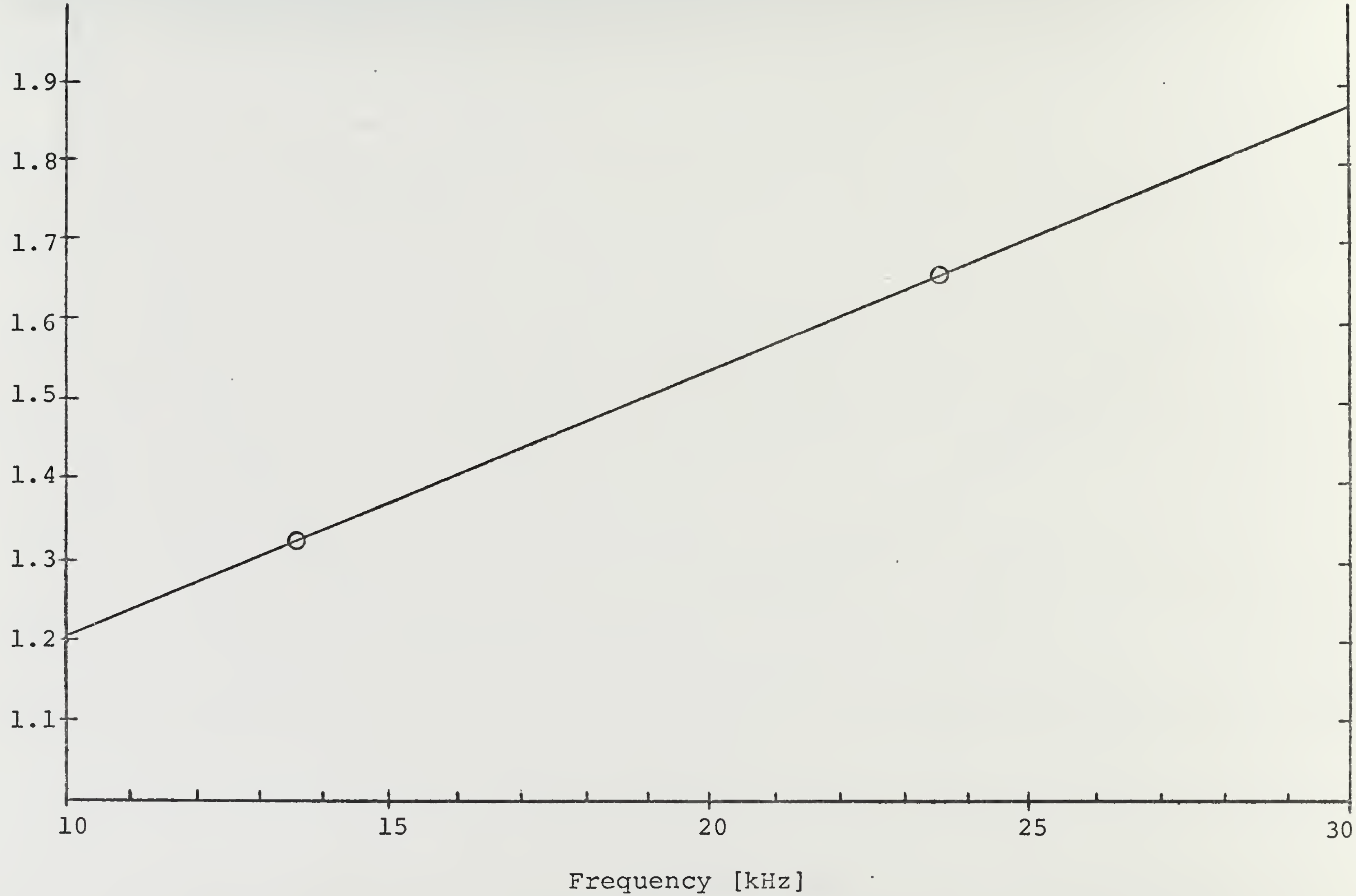

Figure 10. "c" Sea Route.

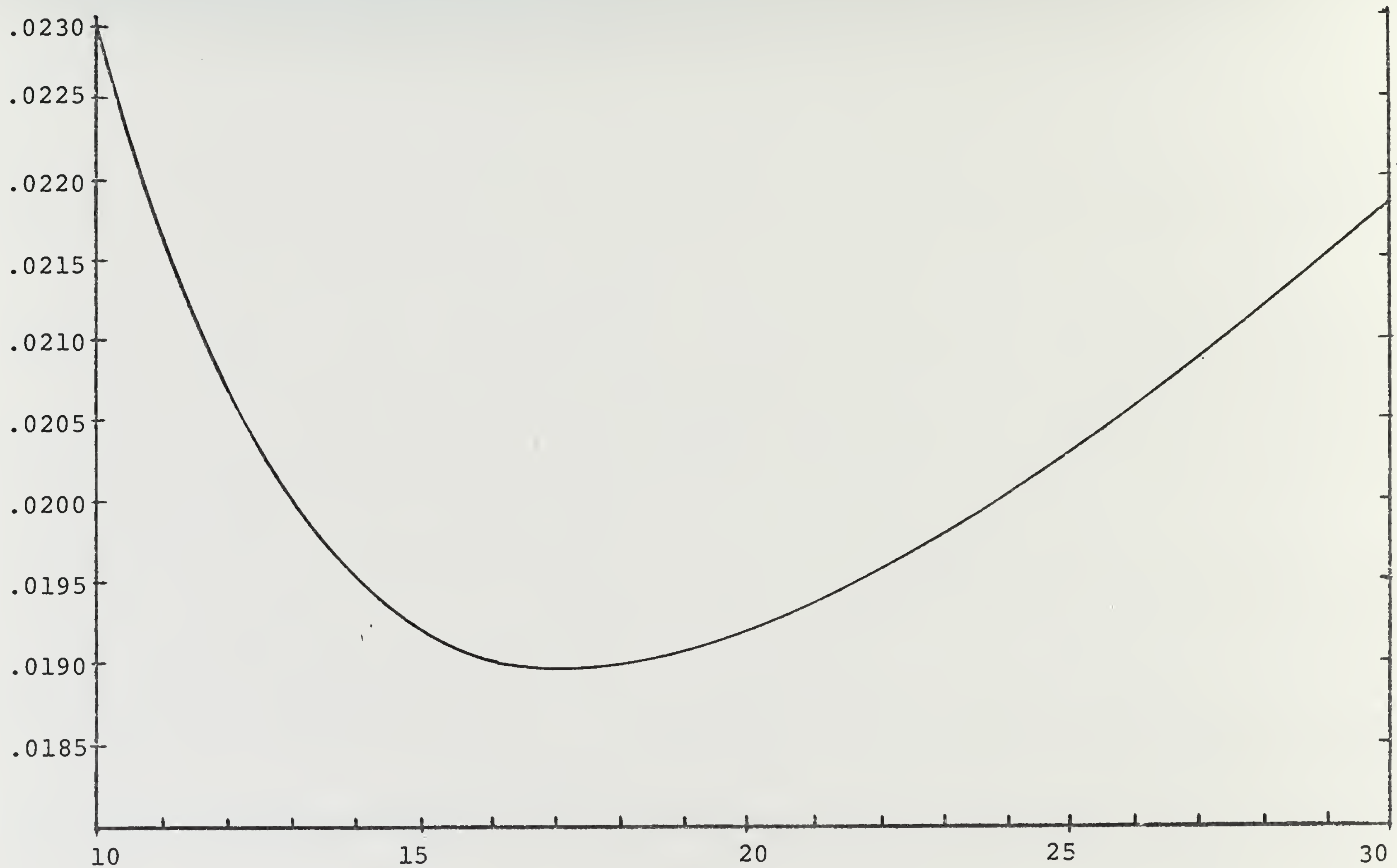

Figure 11. C_V Sea Route.

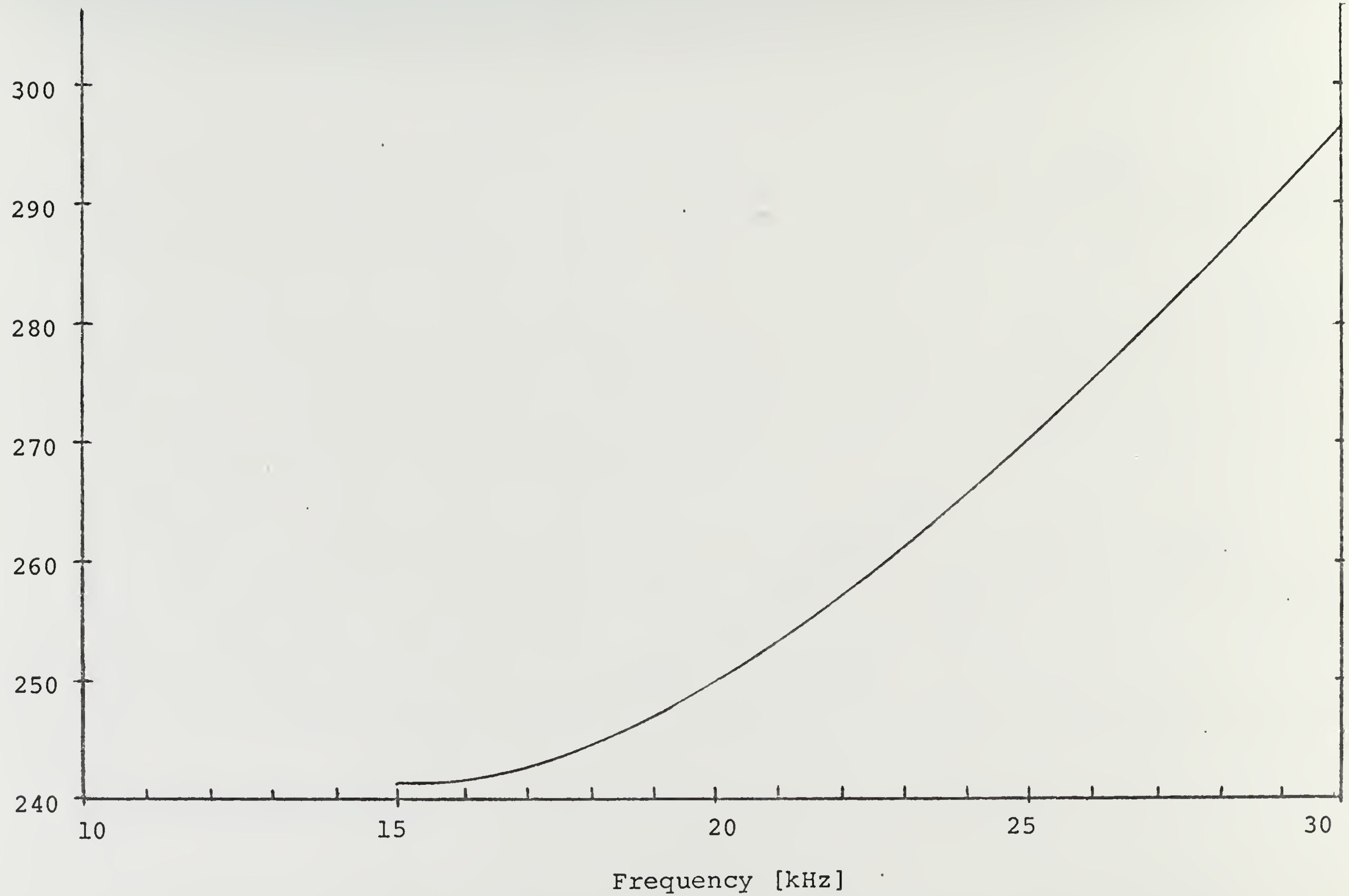

Figure 12. Reference Curve.

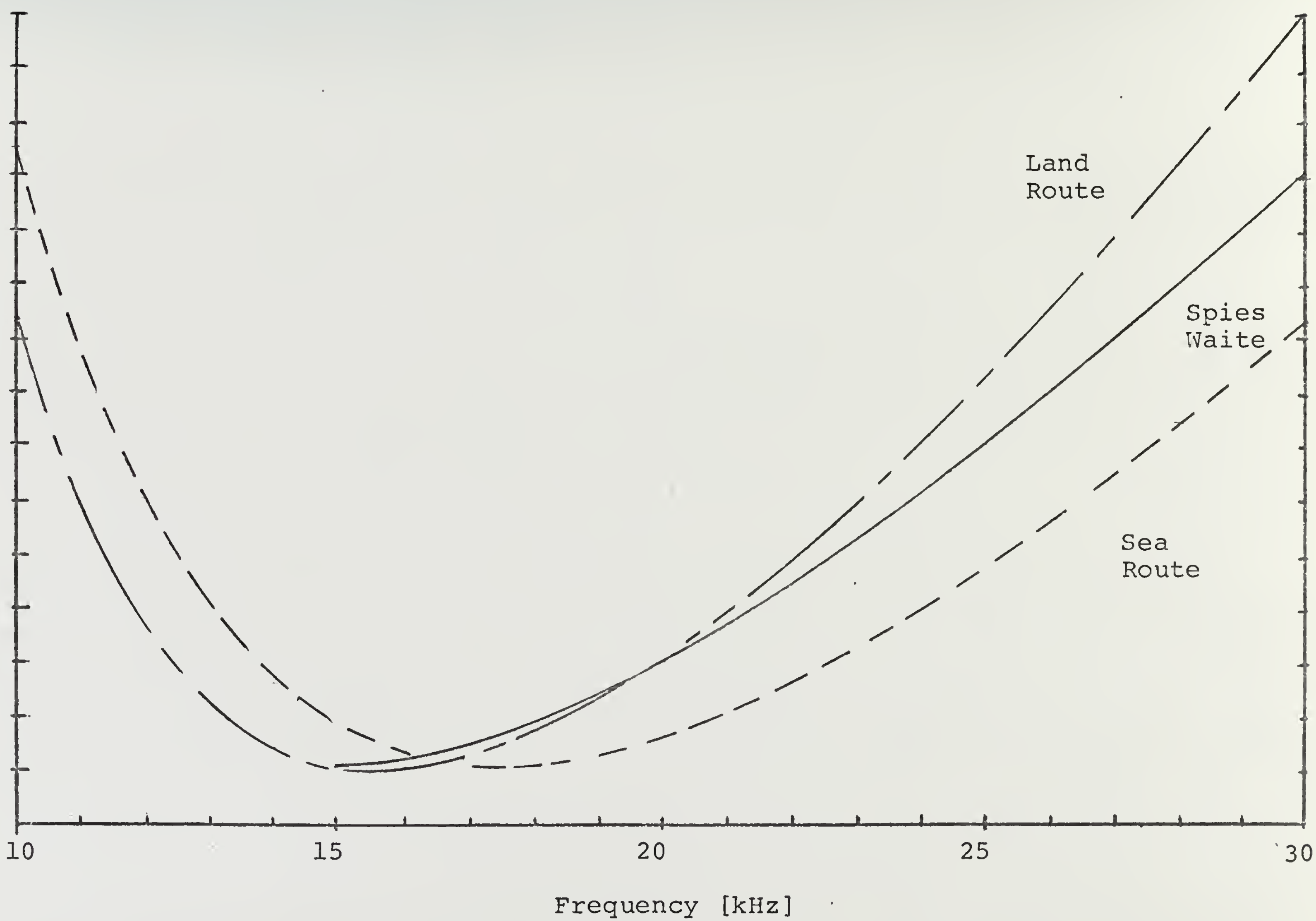

Figure 13. Comparison Curves.

nautical miles. The diurnal shift due to the land portion is equal to 2000 x 0.0133 or 26.6 microseconds. The diurnal shift due to the seawater portion is equal to 4000 x 0.0196 or 78.4 microseconds. The total diurnal shift for this path is 105.0 microseconds.

VII. TABLES OF POSITIONS

In order to use this system of navigation, tables of positions must be generated that will allow the navigator to convert the measured changes in signal phase to geographic coordinates.

Since this system is based on relative changes in signal phase, some standard procedure must be adopted for the navigational tables. This investigation used the great circle distance in nautical miles from a known position to the transmitter. (This distance is also listed in microseconds to facilitate the plotting of new positions. The generated tables also list the bearing of the transmitter and a second bearing, 90 degrees from the first to aid the navigator in laying down lines of position on charts and plotting sheets.)

The known points are spaced every fifteen minutes of latitude and longitude to reduce the need for interpolation over large distances.

Contained in the Computer Output section is a sample page from the tables. Across the top of the page is the name of the transmitting station, its frequency, and geographic location. Latitude is given in the left most and right most columns, and longitude is denoted in the first row. For any given position, there are four entires. The first line is

the great circle distance in nautical miles to the transmitter. The second line contains the same distance expressed in micro-seconds. The third line contains two entries, the first is the bearing to the station along the great circle path, and the second is a bearing to be used to lay down a very good approximation to the circular line of position. The navigator will be concerned with the bearing of the transmitter along the great circle path, in order to have the "zero phase change window" of the cardiod shaped radiation pattern pointed in the proper direction. Also, when the ship is located in the multi-path zone, knowledge of this bearing will allow the radiation pattern null to be pointed at the long path or undesired path signal.

The method of calculation of the tables is a FORTRAN IV program, contained in the Computer Program section which was run on an XDS 9300 computer located at the Naval Postgraduate School. The mathematical model was derived from Ref. [10]. The program computes two quantities, the distance and true bearing from a known geographic position to a transmitter. The calculations are based on the following two equations.

$$\text{hav } D = \text{hav } DLo \cos L_1 \cos L_2 + \text{hav } l$$

$$\text{hav } C = \sec L_1 \csc D \; (\text{hav co}L_2 - \text{hav}(D\sim \text{co}L_1))$$

The function hav (haversine) of an angle is equal to the sine squared of half the angle (hav A = $\sin^2 \frac{1}{2}A$). The quantities in the equations are as indicated below. Figure 14 shows the basic navigational triangle as it appears in this case.

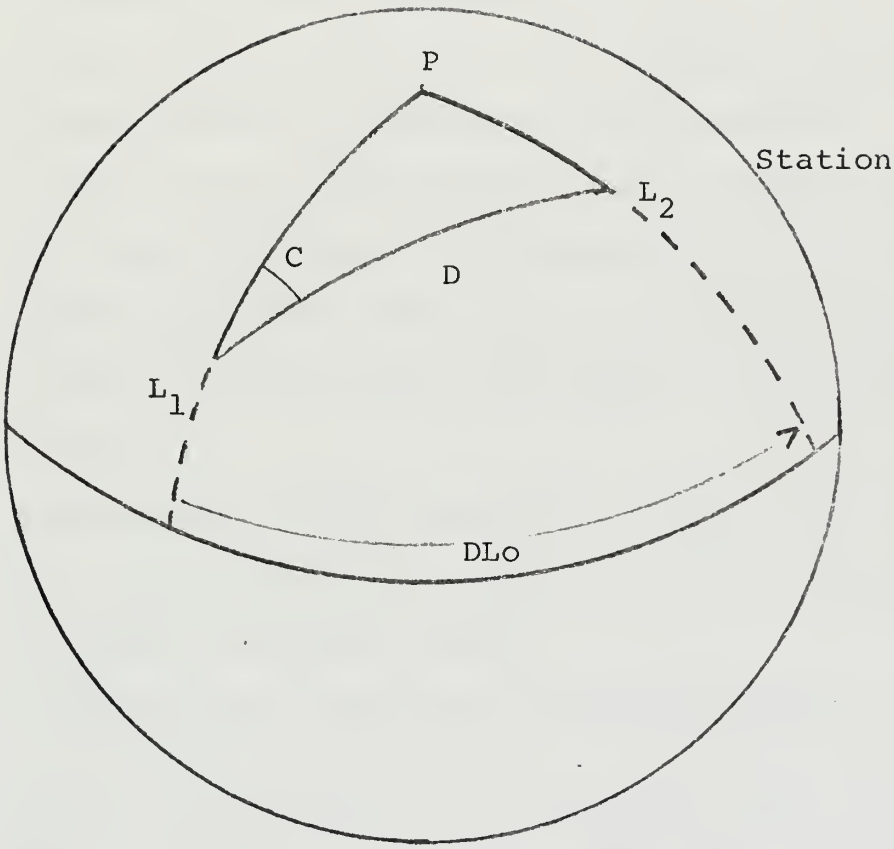

Figure 14. Solid Geometry Navigational Triangle.

D - distance expressed in degrees between the known position and the transmitter

DLo - difference in longitude measured from the known position to the transmitter, and identified as either east or west (This quantity will be less than 180 degrees.).

L_1 - latitude of the known position

L_2 - latitude of the transmitter

l - difference in latitude (l is measured from the known position latitude to the transmitter latitude and identified as either north or south.).

C - an angle indicating the direction of the transmitter from the known position labeled north or south to agree with L_1 and east or west to agree with DLo

CoL_2- colatitude of the transmitter ($CoL_2 = 90 - L_2$ are of the same name, and $CoL_2 = 90 + L_2$ if L_1 and L_2 are of contrary names)

$D{\sim}coL_1$- the numerical difference between D and coL_1

The computer program processes the angular position data in two formats, degrees and radians. The radian format is necessary for use in the computer angular subroutines. The distance is first calculated and then used as an input for arriving at the bearing to the transmitter. The program includes the necessary logic for determining the correct procedures and labels in the computation of DLo, l, CoL_2, plus the conversion of C into a true bearing.

For the purposes of this investigation, tables were generated for an area of the Pacific Ocean adjacent to the coast of California, centered around Monterey. (The coordinates of this area are from 34N to 40N, and from the coast out to 122W.) These tables are in the same format as that in the Computer Output section, and are in the custody of the Dean of Research Administration at the Naval Postgraduate School, Monterey, California. Similar tables may be produced for any other area of interest by using the proper geographic locations as input data for the computer program.

VIII. VLF NAVIGATION SYSTEM

Herein is a listing of the navigation system components and a discussion of their properties and characteristics as they apply to the system. The units are referred to by their manufacturers and model numbers. These particular components were used in this investigation since they were available at the Naval Postgraduate School. Similar units from other manufacturers meet the requirements for this system and will provide the needed performance.

A. COMPONENTS

The basic shipboard system consists of the following items:

One stable oscillator

Three VLF phase tracking receivers

One VLF whip (sense) antenna

One VLF crossed loop antenna

One antenna control unit

1. Stable Oscillator

The very heart of the shipboard system is the stable oscillator. The stability of this oscillator will provide the mark and measure of the system accuracy. The transmitters listed in Table III all have a frequency stability of 1 part in 10^{11} (The meaning of "1 part in 10^{11}" is that for a given oscillator or standard, the output frequency will deviate at the most 1 hertz in 10^{11} hertz from the nominal value) [12].

STATION	FREQ (KHZ)	LOCATION	SPONSOR	TYPE OF TRANSMISSION
GBR	16.0	Rugby, England 52-22 N 1-11 W	British Post Office	CW 1-5 KW
NAA	17.8	Cutler, Maine 44-38.9N 67-16.9W	U. S. Navy	FSK for two hours followed by CW for one hour 1,000 KW
NLK	18.6	Jim Creek, Wash. 48-12.2N 121-55.0W	U. S. Navy	FSK 250 KW
WWVL	20.0	Boulder, Colo. 40-40.9N 105-02.9W	National Bureau of Standards	CW 5 KW
NSS	21.4	Annapolis, Md. 38-59.1N 76-27.2W	U. S. Navy	CW 85 KW
NWC	22.3	N.W.Cape, Aust. 21-49.0S 141-09.8E	U. S. Navy	CW first half hour each even hour followed by FSK for $1\frac{1}{2}$ hours 1,000 KW
NPM	23.4	Lualualei, Hawaii 21-25.5N 158-09.3W	U. S. Navy	FSK 300 KW
NPA	24.0	Balboa, Canal Zone 9-03.3N 79-38.9W	U. S. Navy	FSK 150 KW

TABLE III.

Frequnecy-Stabilized VLF Stations.

As an illustration of system accuracy, let us assume the shipboard oscillator has a stability also of 1 part in 10^{11}. Now given the worst instance where these errors are additive, 2 parts in 10^{11}, examine the system accuracy at this point. Since there are 0.864×10^{11} microseconds in one day, the above error of 2 parts corresponds to 2.32 microseconds. Using the conversion of 6.18 microseconds per nautical mile, and 2000 yards per nautical mile, the maximum error of 2 parts corresponds to 750 yards. If the shipboard oscillator has a stability of 2 parts in 10^{11}, the corresponding maximum error increases to 1125 yards.

Present day frequency standards fall into two general categories, either a high precision temperature controlled crystal, or a device utilizing a natural atomic resonance. There are two stable oscillators located at the Naval Postgraduate School, one each of the types mentioned above, both of which are suitable for system use.

The high quality quartz crystal oscillator is a Model 2.5, manufactured by the Sulzer Laboratories of Rockville, Maryland. This unit requires a 22-32 VDC, 0.33 ampere input, with outputs (1 volt to 50 ohms) at frequencies of 2.5 mHz, 1 mHz, and 100 kHz. The crystal unit operates at 2.5 mHz and is kept at a constant temperature by means of a two stage oven [13]. The crystal will drift with age, and monitoring of its output is necessary to determine the amount of drift.

Prior to use of this type of crystal oscillator, it is necessary that the unit be in operation for periods from 3

to 6 months for settling. Loss of power to the unit will require the long stabilization procedure. Therefore, this type of oscillator is generally powered from wet cell batteries, which are constantly on charge from a normal power supply. On loss of power, the oscillator is then completely carried by the batteries.

Atomic resonance type standards utilize the emitted energy of a given natural decay transition as a basis of frequency definition. The Model V-4700 Rubidium vapor frequency standard manufactured by Varian Associates of Palo Alto, California, uses a hyperfine transition of Rubidium 87 to stabilize a 5 mHz crystal oscillator [14]. This unit has outputs of 5 mHz, 1 mHz, and 100 kHz. It has a long term stability of 5 parts in 10^{11}, and a short term stability of 1 part in 10^{11}. The Varian model uses a similar power supply as the Sulzer crystal unit. The atomic resonance type standards require only a few days for the stabilization process as compared to the months required for crystal units.

The Sulzer crystal has a short term stability of 8 parts in 10^{11}, which would correspond to a maximum error of 3375 yards. This amount of error is greater than an amount to be tolerated for the system. On this basis, a stability of 4 parts in 10^{11} would provide accuracy of less than one nautical mile.

In the selection of a frequency standard, one has the option of either type of the two discussed above or perhaps

a Cesium standard. Two performance characteristics must be evaluated, stability (or inversely dispersion) and drift. The Cesium standard has no drift but a moderate dispersion. The dispersion problem could be remedied by suitable averaging (integration) techniques, but the prime drawback for use in this navigation system is its high cost. Going to a Rubidium standard, the dispersion factor is improved (reduced), but drift now enters the picture. This adds the requirement for continual correction to maintain an accurate standard. Use of a highly precise crystal has the same problems as the Rubidium standard, but with greater drift.

Therefore, with both of the practical standards, drift must be determined by comparison with a refined standard. Depending on the amount of drift and the smallest correction that may be made to the particular frequency standard, a regular correction procedure must be conducted to maintain an accurate navigation system.

2. <u>VLF Tracking Receivers</u>

TRACOR Series 599 VLF Tracking Receivers, manufactured by TRACOR, Incorporated of Austin, Texas, were used in this investigation. These receivers were designed for time and frequency measurements with the VLF transmitting stations listed in Table III.

Figure 15 is a simplified block diagram that depicts the operation of phase tracking VLF receivers. As illustrated, the output of the phase comparator is the input of the electronic phase shifter. The circuit is such that the phase error is driven to zero, and the system tracks an internal null.

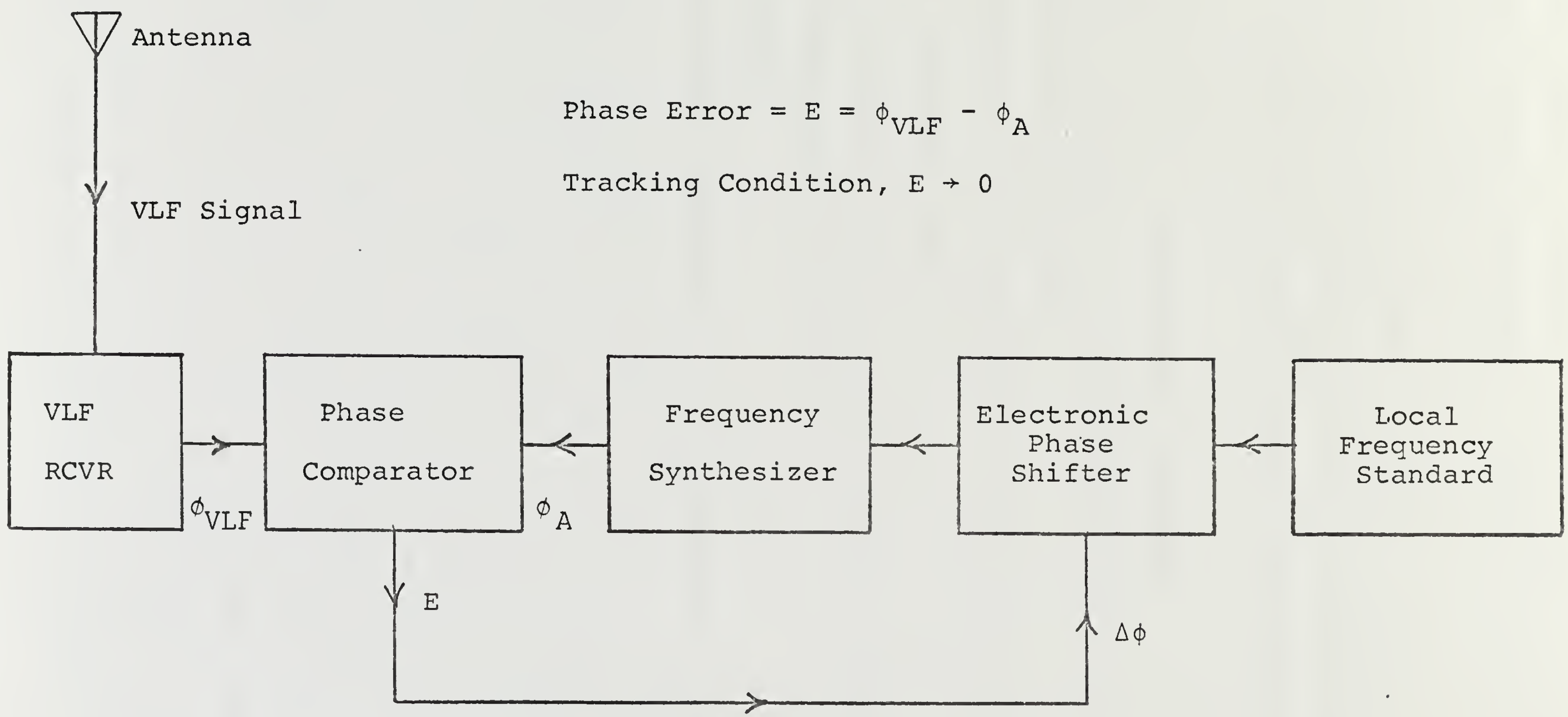

Figure 15. Simplified Block Diagram of VLF Phase Tracking Receiver.

This receiver is powered either from 120 VAC(48-400 Hz) or from a suitable DC source. Useful outputs of this receiver are as follows:

a) time difference register - a digital counter that indicates the relative phase difference in microseconds between the received VLF carrier and the local frequency standard.

b) audio - 1 kHz intermediate frequency.

c) phase difference (100 microsecond scale) for display on an external chart recorder.

d) relative carrier level from a front panel meter and also from a recorder output.

The receiver requires a 0.01 microvolt signal at its terminals to enable normal phase tracking [15].

3. Antennas

The sensing apparatus for this navigation system consists of three separate antennas. Two loop antennas are concentrically mounted at right angles in a submarine VLF antenna. This antenna is designated as an AT-317C/BRR (frequency range of 14.6 - 38.0 kHz). For a shipboard installation, one loop is aligned with the ship's centerline, and the other loop is at a right angle or running port and starboard. Each of these loops has a separate but identical cable run to the Antenna Control Unit. A VLF whip antenna (TRACOR Model No. 599800) is also used to provide a sense input to obtain the desired antenna radiation pattern. The only requirement placed on the location of the whip antenna relative to the

loop antennas, is that the distance should be small compared to a wavelength. This requirement provides no restriction when operating at VLF frequencies.

4. Antenna Control Unit

The Antenna Control Unit consists of the Antenna Control Console, the two cardiod units, plus the associated auxiliary components. Its purpose is to combine the signals from the three antennas into an effective single antenna signal. The resulting antenna pattern is to be rotatable to allow the ship freedom of motion to maneuver, and also to allow the navigator the freedom of choice to change the station being tracked. Therefore, a gyro compass repeater signal is utilized to provide the direction sense, and an antenna pattern control capability. An earlier section discussed the actual operation and performance of the components and the unit as whole.

B. SYSTEM

Figure 16 depicts the components of the navigation system and their interconnection. Two rotatable antenna radiation patterns (formed by means of the three antennas, the resolvers, and the cardiod units) sense VLF signals. These detected signals are compared in the phase-traking receivers with the local standard through the use of an internal frequency synthesizer and a phase-lock loop technique. The phase difference (a relative quantity) is read out on a digital indicator on the face of the receiver, and/or displayed on a continuous graph recorder as a function of time. The output

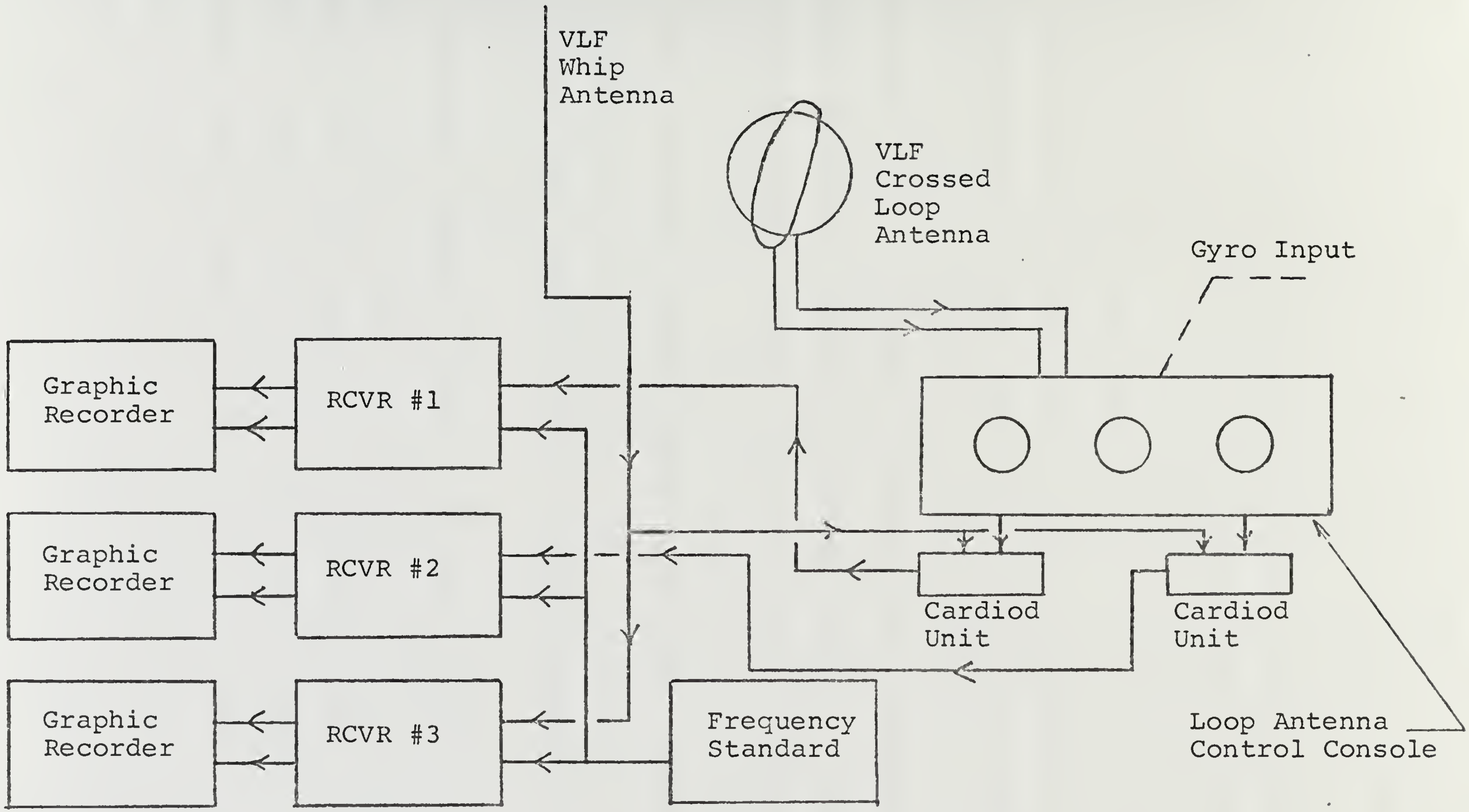

Figure 16. VLF Long Range Navigation System Components and Their Interconnections.

format of the phase difference is in microseconds of change, which may be converted to distance traveled by the conversion unit of 6.18 microseconds per nautical mile, or through the use of tables.

While Figure 16 shows RCVR #3 being fed from the whip antenna, a third resolver channel can be used to increase the system flexability. The whip signal is useful only in the single mode for a transmitter.

The antenna radiation pattern must be capable of tracking the transmitter to insure that the received VLF signal enters through the zero phase change window on its axis. To achieve this capability, it is best to consider the components of the antenna patterns. The cardiod-shaped pattern is composed of the "figure eight" pattern from the "single effective loop" and the whip pattern. The cardiod orientation is the same as that of the loop antenna pattern, and this is controlled by the position of the resolver rotor. Therefore, the means of rotating the resultant cardiod-shaped pattern is to rotate the resolver rotor.

As course changes are made, the ship "rotates" under the rotor of the gyro compass, which maintains its orientation. Likewise, the true bearing to a transmitter will not change with the ship's course change (the relative bearing measured from the ship's head or bow will change an amount equal to the course change). Therefore, by controlling the position of the resolver rotor with a gyro repeater input, the antenna pattern will remain pointed at the transmitter regardless of the

ship's maneuvers. Small corrections will be made as the ship traverses large distances, and the bearings to each trans-metter changes. Tables of known positions, discussed in the next section, will contain these bearings. The navigator need only make these changes to the resolver indicators.

IX. NAVIGATIONAL FORMS AND PROCEDURES

A. FORMS

Four new navigational forms are proposed for use with the VLF navigation system. Their purposes and use are explained in the following sections.

Reference Position Form

This form, Figure 17, records a position that is fixed by outside means. The form has a space to record the oscillator drift in microseconds per day. The entry would be that determined by the last calibration check. Space is provided for a description of the method of fixing the ship's position, also. Typically, at the start of a voyage, an appropriate location can be used as a starting reference. At the time of the navigational fix, the receiver microsecond output is recorded. Space is provided for the recording of the geographic line of position in microseconds from the table of positions. Δ is the numerical difference in the receiver output and the table of position value, such that Δ may be added to the receiver reading (also plus corrections) to obtain the proper chart value for plotting purposes.

Hourly Navigation Record

This form, Figure 18, provides the main log for hourly recording of the ship's location. The receiver output is

DATE ____________________

TIME ____________________

POSITION ________________

____

RCVR #1	RCVR #2	RCVR #3
STATION __________	STATION __________	STATION __________
RCVR RDG ________	RCVR RDG ________	RCVR RDG ________
TABLE ___________	TABLE ___________	TABLE ___________
Δ _______________	Δ _______________	Δ _______________
OFFSET __________	OFFSET __________	OFFSET __________

OSCILLATOR DRIFT ______________________

DESCRIPTION OF FIX ________________________

____

____

____

____

FIGURE 17. Reference Position Form.

DATE ____________

	STA #1			STA #2			STA #3			
	Δ =			Δ =			Δ =			
TIME	RCVR	CORRT	CHART	RCVR	CORRT	CHART	RCVR	CORRT	CHART	POSIT
0100										
0200										
0300										
0400										
0500										
0600										
0700										
0800										
0900										
1000										
1100										
1200										
1300										
1400										
1500										
1600										
1700										
1800										
1900										
2000										
2100										
2200										
2300										
2400										

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Δ t CORRECTIONS

TIME	ΔT	TIME	ΔT	TIME	ΔT

Figure 18. Hourly Navigation Record.

entered in the column labelled "RCVR". The total correction to the receiver output is entered in the next column labelled "CORRT". This should include Δ, oscillator drift, and Δt if appropriate for that particular time of the day. The hourly position may be entered in the two extreme right hand columns. Sufficient space is provided at the bottom of the form to allow the navigator to record the predicted values for Δt for night navigation.

Sunset/Sunrise Calculation Forms

These two forms, Figures 19 and 20, are used to calculate the time of sunset/sunrise at ionospheric heights. Both forms are self explanatory, and are based on the work of Brady and Crombie [9]. Appendix A is a collection of useful data for use with these two forms.

B. PROCEDURES

Navigation procedures can best be described in a narrative type discussion of a navigator's use of this sytem.

Prior to the actual use of the navigation system, the navigator selects two or more transmitting stations for tracking. Among the things to be considered in his selection are bearings to the stations in the area where the ship will be steaming, scheduled transmitter maintenance periods, transmitter power, and distance to the station. Bearings and distance to the transmitting stations will be listed in the tables of position. Stations should be selected so that their bearings will cross at least 30 degree angles (preferrable as close to 90 degrees as possible) to insure maximal accuracy.

SUNSET

DATE__________

L __________

λ __________

δ __________

GHA(1200) __________

SIN L __________ A

COS L __________ C

SIN δ __________ B

COS δ __________ D

$$\text{COS(LHA)} = \frac{-.1103 - A \times B}{C \times D}$$

$$\text{LHA} = \frac{(\text{LHA})}{15}$$

GHA < 180 or GHA > 180

$$E = \frac{-\text{GHA}}{15} \qquad E = \frac{360-\text{GHA}}{15}$$

$$\theta_D = \frac{\lambda}{15}$$

+	-
12.0000	XXXXXXX
E	
θ_D W	E
LHA	XXXXXXX

TS __________

L __________

λ __________

δ __________

GHA(1200) __________

SIN L __________ A

COS L __________ C

SIN δ __________ B

COS δ __________ D

$$\text{COS(LHA)} = \frac{-.1103 - A \times B}{C \times D}$$

$$\text{LHA} = \frac{(\text{LHA})}{15}$$

GHA < 180 or GHA > 180

$$E = \frac{-\text{GHA}}{15} \qquad E = \frac{360-\text{GHA}}{15}$$

$$\theta_D = \frac{\lambda}{15}$$

+	-
12.0000	XXXXXXX
E	
θ_D W	E
LHA	XXXXXXX

TS __________

(L and δ are positive if North, and negative if South)

FIGURE 19. Sunset Calculation Form.

SUNRISE

__________ DATE __________ __________

L __________	L __________
λ __________	λ __________
δ __________	δ __________
GHA(1200) __________	GHA(1200) __________
SIN L __________ A	SIN L __________ A
COS L __________ C	COS L __________ C
SIN δ __________ B	SIN δ __________ B
COS δ __________ D	COS δ __________ D
$\text{COS(LHA)} = \frac{-.1276 - A \times B}{C \times D}$	$\text{COS(LHA)} = \frac{-.1276 - A \times B}{C \times D}$
$\text{LHA} = \frac{\text{(LHA)}}{15}$	$\text{LHA} = \frac{\text{(LHA)}}{15}$
GHA < 180 or GHA > 180	GHA < 180 or GHA > 180
$E = \frac{-\text{GHA}}{15}$ $E = \frac{360-\text{GHA}}{15}$	$E = \frac{-\text{GHA}}{15}$ $E = \frac{360-\text{GHA}}{15}$
$\theta_D = \frac{\lambda}{15}$	$\theta_D = \frac{\lambda}{15}$
+ -	+ -
12.0000 XXXXXXX	12.0000 XXXXXXX
E __________	E __________
θ_D W E	θ_D W E
LHA XXXXXXX	LHA XXXXXXX
______ ______	______ ______
______	______
TR __________	TR __________

(L and δ are positive if North, and negative if South)

FIGURE 20. Sunrise Calculation Form.

The distance to a transmitting station should be greater than 2400 nautical miles to insure that the receiver is tracking the principal mode of the transmitting station. The Time Service Announcement of the U. S. Naval Observatory, a sample of which is reproduced as Table IV, is a necessary document for the navigator's use.

It is also necessary that the navigator know the amount of frequency offset between his local standard and reference oscillators for the stations to be tracked. This offset should be expressed in microseconds and must be applied daily to the output of the receivers. As an exampled of this correction, suppose that the transmitter reference oscillator is ahead of the local standard by 1 part in 10^{11}. This corresponds to a daily correction of 1.16 microseconds to be added to the output data (phase difference) of the particular receiver tracking that transmitter. Similar appropriate corrections will be applied to the other receiver outputs.

After the stations have been chosen, the navigator will check the antenna field intensity radiation patterns, and commence receiver tracking. As the ship gets underway, the necessary information is entered in the Reference Position Form. As time progresses, appropriate entires are made in the Hourly Navigation Record. As stated earlier the value of the oscillator drift was recorded on the Reference Position Form. Care must be taken to insure that this correction and that for frequency offset are properly applied.

U. S. NAVAL OBSERVATORY
WASHINGTON, D. C. 20390

14 October 1969
(Supersedes T. S. Ann. of 27 September 1968)
NO. 18

TIME SERVICE ANNOUNCEMENT, SERIES 3

SCHEDULE OF TIME AND FREQUENCY TRANSMISSIONS
ON VLF FROM U. S. NAVAL RADIO STATIONS

1. The following schedule is in effect:

Station	Location	Frequency (kHz)*	Nominal Radiated Power (kw)	Maintenance	Special Transmissions
NAA	Cutler, Maine 44°38!9N, 67°16!9W	17.80	1,000 (1)	1400 to 1800 UT each Friday	FSK for two hours followed by CW for one hour. Phase stable on 17.80 but not on 17.80 kHz.
NBA	Balboa, Canal Zone 09°03!3N, 79°38!9W	24.00	150 (2)	1200 to 1800 UT each Monday	Time signals on CW Morse from 55 to 60th minute every even hour except 2355 to 2400 UT. FSK continuous at other times. Phase stable on 24.00 but not on 24.05 kHz.*

Station	Location	Frequency (kHz)*	Nominal Radiated Power (kw)	Maintenance	Special Transmissions
NLK	Jim Creek, Wash. 48°12!2N, 121°55!0W	18.60	250	1000 to 1500 UT second Thursday of each month	FSK continuous except five minutes before each hour on locked key. Phase stable on 18.60 but not on 18.65 kHz.*
NPM	Lualualei, Hawaii 21°25!5N 158°09!3W	23.40	140	1700 UT Monday to 0200 UT Tuesday 1st & 3rd Monday of each month	FSK continuous. Phase stable on 23.40 but not on 23.45 kHz.*
NSS	Annapolis, Md 38°59!1N, 76°27!2W	21.40	85	1300 to 1900 UT each Wednesday	Time signals from 55 to 60th minute each hour. CW More continuous. Phase stable.
NWC	North West Cape Australia 21°49!0S, 114°09!8E	22.30	1,000	0000 to 0300 UT each Monday (3)	FSK and CW. Phase stable on 22.30 but not on 22.35 kHz.* (4)

TABLE IV - Time Service Announcement.

The navigator will calculate the time of sunset for each of the transmitting stations using a Sunset Calculation Form. Using the ship's speed and course, he will estimate his position at ionospheric sunset, and calculate this time of sunset. These calculation will require the use of the Nautical Almanac to determine the declination and the 1200 Greenwich Hour Angle for the sun. Now using a modified version of Wait's equation for the amount of diurnal shift (the equation now allows the use of distance in nautical miles) we arrive at the value of Δt.

$$\Delta t = D\, C_v$$

The value of D is readily accessible from the tables of position. Again using predicted course and speed, the various times of sunrise may be computed. C_v is obtained from Figures 4 and/or 6, depending on the propagation path. Sufficient information is now at hand for the diurnal shift prediction trapezoid. The trapezoid must be modified to indicate a slope due to the motion of the ship with respect to the transmitting station. The amount of correction for each hour is N times 6.18 microseconds, where N is the ship's speed component in knots toward (minus correction) or away from (plus correction) the transmitter. With the construction of the modified trapezoid completed, the hourly corrections are entered on the bottom of the Hourly Navigation Record for use at the required time.

As an illustration of the accuracy of this method for the prediction of Δt, Table V lists the following results for two stations, NPM and NAA.

TABLE V
TRAPEZOID PREDICTION RESULTS

NPM

frequency - 23.4 kHz

propagation path - seawater

predicted Δt - 41.2 microseconds

mean error - 2.5 microseconds (810 yards)

NAA

frequency - 17.8 kHz

propagation path - land

predicted Δt - 30.3 microseconds

mean error - 2.1 microseconds (680 yards)

In the above two examples, mean error is equal to the average of the absolute values of the differences between the predicted trapezoid and the recorded diurnal shift. Samples of the differences were taken every fifteen minutes during the period that diurnal shift was present.

Occasionally, it is necessary for transmitting stations to make offsets to their master oscillators to stay in tolerance with the national standard. These offsets are scheduled well in advance of their accomplishment. The navigator must make a similar correction to his readings at the same time as the actual offset is applied to maintain a tracking navigation system. This offset is applied only if navigation is in process. This correction can be ignored when starting from a new reference position, since in this case, the offset is then included in the Δ value.

APPENDIX A

STATIONS

NPM	NAA
L = 21-25.5N	L = 44-38.9N
λ =158-09.3W 158.1550W	λ = 67-16.9W 67.2817W
A = .3652	A = .7028
C = .9308	C = .7114
θ_D = 10.5437W	θ_D = 4.4854W

NBA	NSS	NWC
L = 09-03.3N	L = 38-59.1N	L = 21-49.0S
λ = 79-38.9W 79.6483W	λ = 76-27.2W 76.4533W	λ =114-09.8E 114.1633E
A = .1574	A = .6291	A =-.3716
C = .9876	C = .7773	C = .9284
θ_D = 5.3099W	θ_D = 5.0969W	θ_D = 7.6109E

GBR	NLK	WWVL
L = 52-22N	L = 48-12N	L = 40-40N
λ = 1-11W 1.1833W	λ =121-55W 121.9167W	λ =105-02W 105.0333W
A = .7919	A = .7455	A = .6517
C = .6106	C = .6665	C = .7585
θ_D = .0789W	θ_D = 8.1278W	θ_D = 7.0022W

Time or λ in Decimals	Time or λ in Minutes
.0000	00
.0083	
.0167	01
.0250	
.0333	02
.0416	
.0500	03
.0583	
.0667	04
.0750	
.0833	05
.0916	
.1000	06
.1083	
.1167	07
.1250	
.1333	08
.1416	
.1500	09
.1583	
.1667	10
.1750	
.1833	11
.1916	
.2000	12
.2083	
.2167	13
.2500	
.2333	14
.2416	
.2500	15
.2583	
.2667	16
.2750	

Time or λ in Decimals	Time or λ in Minutes
.0017	.1
.0033	.2
.0050	.3
.0067	.4
.0083	.5
.0100	.6
.0117	.7
.0133	.8
.0150	.9

Time or λ in Decimals	Time or λ in Minutes
.2833	17
.2916	
.3000	18
.3083	
.3167	19
.3250	
.3333	20
.3416	
.3500	21
.3583	
.3667	22
.3750	
.3833	23
.3916	
.4000	24
.4083	
.4167	25
.4250	
.4333	26
.4416	
.4500	27
.4583	
.4667	28
.4750	
.4833	29
.4916	
.5000	30
.5083	
.5167	31
.5250	
.5333	32
.5416	
.5500	33
.5583	

Time or λ in Decimals	Time or λ in Minutes
.5667	34
.5750	
.5833	35
.5916	
.6000	36
.6083	
.6167	37
.6250	
.6333	38
.6416	
.6500	39
.6583	
.6667	40
.6750	
.6833	41
.6916	
.7000	42
.7083	
.7167	43
.7250	
.7333	44
.7416	
.7500	45
.7583	
.7667	46
.7750	
.7833	47
.7916	
.8000	48
.8083	
.8167	49
.8250	
.8333	50
.8416	

Time or λ in Decimals	Time or λ in Minutes
.8500	51
.8583	
.8667	52
.8750	
.8833	53
.8916	
.9000	54
.9083	
.9167	55
.9250	
.9333	56
.9416	
.9500	57
.9583	
.9667	58
.9750	
.9833	59
.9916	
1.0000	60

NPM 23.4 KHZ 21-25N 158-09W

LATITUDE NORTH	LONGITUDE WEST 114-00	114-15	114-30	114-45
00-00	2885.37 17831.57 299.4/029.4	2872.30 17750.84 299.5/029.5	2859.26 17670.20 299.6/029.6	2846.22 17589.65 299.7/029.7
00-15	2878.03 17786.22 299.2/029.2	2864.94 17705.34 299.3/029.3	2851.87 17624.54 299.4/029.4	2838.81 17543.83 299.5/029.5
00-30	2870.74 17741.15 298.0/029.0	2857.62 17660.11 299.1/029.1	2844.52 17579.16 299.2/029.2	2831.44 17498.30 299.3/029.3
00-45	2863.49 17696.36 298.8/028.8	2850.35 17615.17 298.9/028.9	2837.23 17534.07 299.0/029.0	2824.12 17453.04 299.1/029.1
01-00	2856.29 17651.86 298.6/028.6	2843.13 17570.52 298.7/028.7	2829.98 17489.26 298.8/028.8	2816.84 17408.08 298.9/028.9
01-15	2849.13 17607.63 298.4/028.4	2835.95 17526.14 298.5/028.5	2822.77 17444.74 298.6/028.6	2809.61 17363.41 298.7/028.7
01-30	2842.02 17563.70 298.2/028.2	2828.81 17482.06 298.3/028.3	2815.62 17400.50 298.4/028.4	2802.43 17319.03 298.5/028.5
01-45	2834.96 17520.05 298.0/028.0	2821.73 17438.27 298.1/028.1	2808.51 17356.57 298.2/028.2	2795.30 17274.94 298.3/028.3
02-00	2827.94 17476.70 297.8/027.8	2814.69 17394.77 297.9/027.9	2801.44 17312.92 298.0/028.0	2788.21 17231.15 298.1/028.1
02-15	2820.98 17433.64 297.6/027.6	2807.70 17351.57 297.7/027.7	2794.43 17269.58 297.8/027.8	2781.17 17187.66 297.9/027.9
02-30	2814.06 17390.87 297.4/027.4	2800.75 17308.67 297.5/027.5	2787.46 17226.53 297.6/027.6	2774.19 17144.47 297.7/027.7
02-45	2807.19 17348.41 297.2/027.2	2793.86 17266.06 297.3/027.3	2780.55 17183.78 297.4/027.4	2767.25 17101.58 297.5/027.5

```
C     THIS PROGRAM COMPUTES TABLES OF POSITIONS
      DIMENSICN CPM(36,8), OBM(36,8)
      READ (5,3) ALATS, ALNGS
    3 FORMAT (2F10.5)
      READ (5,3) ALAT, ALNG
      AMALT = 40.
      ALNG1 = ALNG
      IAB = 34
    7 IF (ALAT.GE.AMALT)  GO TO 650
      II = 1
      DO 500  I = 1, 12
      DO 400  J = 1, 8
      RALAT = ALAT/57.29578
      RALATS = ALATS/57.29578
      IF (ALNGS.GE.0.0)  GO TO 10
      IF (ALNG.LT.0.0)  GC TO 11
      DLO = ALNGS - ALNG
      ADLO = ABS(DLO)
      IF (ADLO.GE.180.)  DLO = 360. + DLO
      GO TO 13
   10 IF (ALNG.GE.0.0)  GO TO 11
      DLO = ALNGS - ALNG
      IF (DLO.GE.180.)  DLO = -360. + DLO
      GO TO 13
   11 DLO = ALNGS - ALNG
      GO TO 13
   13 ADLO = ABS(DLO)
      CONTINUE
      HADLO = C.5*ADLO/57.29578
      THE = SIN(HADLO)*SIN(HADLO)*COS(RALAT)*COS(RALATS)
      DL = ALATS - ALAT
      ADL = ABS(DL)
      HADL = 0.5*ADL/57.29578
      HD = SIN(HADL)*SIN(HADL) + THE
      CD = 1. - 2.*HD
      IF (CD.GT.0.0)  GO TO 15
      B = -CD
      ARGS = B/SQRT(1. - B**2)
      RD = 1.5708 + ATAN(ARGS)
      GO TO 16
   15 ARGC = CD/SQRT(1. - CD**2)
      RD = 1.5708 - ATAN(ARGC)
   16 CONTINUE
      D = RD * 57.29578
      DNM = 60. * D
      DMS = 6.18 * DNM
      CCL1 = 90. - ABS(ALAT)
      AD = D - CCL1
      DCL1 = ABS(AD)
      IF (ALAT.GE.0.0)  GC TO 25
      IF (ALATS.GE.0.0)  GO TO 28
      GO TO 26
   25 IF (ALATS.GE.0.0)  GO TO 26
   28 CCL2 = 90. + ABS(ALATS)
      GO TO 27
   26 COL2 = 90. - ABS(ALATS)
   27 CONTINUE
      HCOL2 = C.5*COL2/57.29578
      HCCL1 = C.5*DCL1/57.29578
      CA = SIN(HCOL2)*SIN(HCOL2) - SIN(HDCL1)*SIN(HDCL1)
      CB = 1./COS(RALAT)
      CC = 1./SIN(RD)
      HCCC = CA * CB * CC
      CCCC = 1. - 2.*HCCC
      ARGCC = CCCC/SQRT(1. - CCCC**2)
      RCCC = 1.5708 - ATAN(ARGCC)
      CCC = RCCC * 57.29578
      IF (ALAT.GE.0.0)  GO TO 30
      IF (DLO.GE.C.0)  GO TO 35
      GO TO 36
   30 IF (DLO.GE.0.0)  GO TO 40
      GC TO 37
```

```
 35 CCC = CCC - 180
    GO TO 40
 36 CCC = CCC + 180.
    GO TO 40
 37 CCC = 360. - CCC
 40 CONTINUE
    BCC = CCC + 90.
    IF (BCC.GT.360.)  BCC = BCC - 360.
    IJ = II + 1
    IK = II + 2
    OPM(II,J) = DNM
    OPM(IJ,J) = DMS
    OPM(IK,J) = CCC
    OBM(IK,J) = BCC
    ALNG = ALNG - 0.25
400 CONTINUE
    ALNG = ALNG1
    II = IK + 1
    ALAT = ALAT + 0.25
500 CONTINUE
    WRITE (6,100)
100 FORMAT (1H1,"NWC",7X,"22.3 KHZ",2X,"21-49.0S",4X,
   1"114-09.8E")
    WRITE (6,101)
101 FORMAT ("LATITUDE",47X,"LONGITUDE WEST",47X,
   1"LATITUDE")
    WRITE (6,102)
102 FORMAT (2X,"NORTH",5X,"124-00",7X,"124-15",7X,
   1"124-30",7X,"124-45",7X,"125-00",7X,"125-15",7X,
   1"125-30",7X,"125-45",9X,"NORTH")
    L = 1
    ICD = 00
    DO 600  K = 1, 36
    GO TO (601,602,603) L
601 WRITE (6,605) IAB,ICD,OPM(K,1),OPM(K,2),OPM(K,3),
   1OPM(K,4),OPM(K,5),OPM(K,6),OPM(K,7),OPM(K,8),IAB,ICD
605 FORMAT (1H0,1X,I2,"-",I2,4X,F8.2,5X,F8.2,5X,F8.2,5X,
   1F8.2,5X,F8.2,5X,F8.2,5X,F8.2,5X,F8.2,8X,I2,"-",I2)
    ICD = ICD + 15
    IF (ICD.EQ.60)  GO TO 615
    GO TO 610
615 ICD = 00
    IAB = IAB + 1
    GO TO 610
602 WRITE (6,606) OPM(K,1),OPM(K,2),OPM(K,3),OPM(K,4),
   1OPM(K,5),OPM(K,6),OPM(K,7),OPM(K,8)
606 FORMAT (11X,8(F8.2,5X))
    GO TO 610
603 WRITE (6,607) OPM(K,1),OBM(K,1),OPM(K,2),OBM(K,2),
   1OPM(K,3),OBM(K,3),OPM(K,4),OBM(K,4),OPM(K,5),OBM(K,5),
   1OPM(K,6),OBM(K,6),OPM(K,7),OBM(K,7),OPM(K,8),OBM(K,8)
607 FORMAT (9X,8(F5.1,"/",F5.1,2X))
    GO TO 610
610 L = L + 1
    IF (L.GT.3)  L = L/3
600 CONTINUE
    GO TO 7
650 WRITE (6,651)
651 FORMAT (1H1)
    END
```

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13. ABSTRACT

The highly stable propagation characteristics of VLF transmissions make them an ideal source of world-wide navigation data. The arrival phase of a VLF signal is continuously compared with a local standard The change in the phase difference between the received signal and the local standard is converted to relative motion with respect to the VLF transmitter.

This investigation concerns itself with the development as a whole of the VLF navigation system. Refinements are made in the antenna system and the antenna signal processing. In addition, navigation procedures, tables, and forms are presented for system use.

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